101112109

Sustainable and Green Electronics for Circular Economy

Deliverable 4.6

Life cycle assessment and handprint study results for select case studies

Project Coordinator	Ramon Caanen, Philips Electronics Nederland B.V.		
Start date Project	June 1st 2023	**Duration**	36 months
Version	2.0		
Status	Final		
Date of issue	29-05-2026		
Dissemination level	Public		

Authors' data

Author	Affiliation	E-mail
David Sánchez	Fraunhofer IZM (FHG)	David.sanchez@izm.fraunhofer.de
Theresa Seeholzer	Infineon Technologies AG (IFAG)	Theresa.seeholzer@infineon.com
Lotta Hepo-oja	VTT Technical Research Centre of Finland Ltd (VTT)	Lotta.hepo-oja@vtt.fi
Ravi Teja Pabbisetty	Philips Electronics Nederland (PEN)	Raviteja.pabbisetty@philips.com
Sharina Ligtelijn	Philips Electronics Nederland (PEN)	Sharina.ligtelijn@philips.com
Sachin Nande	Philips Electronics Nederland (PEN)	Sachin.nande@philips.com
Jasper de Vreede	Philips Electronics Nederland (PEN)	Jasper.de.vreede@philips.com
Philip Monsbourgh	Philips Consumer Lifestyle (PCS)	Philip.monsbourgh@philips.com
Final editor's address	Philips Electronics Nederland (PEN)	Ramon Caanen Philips Electronics Nederland B.V. High Tech Campus 37 5656AE Eindhoven / Netherlands

Management Summary

Purpose and scope

This document presents the results of the Life Cycle Assessment (LCA) for all 10 pilots developed within Sustronics, as well as the results for the handprint analysis performed for a selection of pilots (based on their appropriateness for such an analysis).

This deliverable covers the status of the pilots as of M34. While the development process is still in its finalisation phase (but ongoing), their status as reflected in this deliverable is deemed representative of their fully final stage. It is to be noted however, that in the time remaining until project closure changes in the pilots' designs are still possible.

Methodology and process

All LCAs in this deliverable cover cradle-to-grave in scope and use the EF3.1 Life Cycle Impact Assessment (LCIA) methodology for the calculation of the environmental impacts. Since the LCA of different pilots was performed by different organisations, the tools and databases used vary (they are presented in Section 2).

Certain methodological aspects such as cut-off rules or allocation approaches also differ depending on common practice on each organisation or the specific research interest in every pilot. All LCAs follow the ISO 14040/44 norms for Life Cycle Assessment but due to the research nature of this project, full compliance is not claimed.

These tool and methodological divergences across pilots mean that the results may not be directly comparable. In relative terms however, it can be seen that general trends and impacts distributions do largely converge, and it is on this basis that this document attempts to draw more general conclusions from the LCAs presented. The methodological differences however shall still be kept in mind when interpreting the conclusions.

For each pilot, a full section of the deliverable is devoted. In it, the following sections are explained:

- Introduction. Brief introduction to the pilot and its main contributors.
- Scope of the study. General description of the LCA scope of the pilot.
- Life cycle inventory. Description of the system under study, key assumptions and modelling approach by the practitioner as well as relevant data sources.
- Life cycle impact assessment. Presentation of the LCA results.
- Life cycle interpretation and scenario analysis. Interpretation of the LCA results, sensitivity analysis or other scenario-based additional exploration of the results.
- Conclusions. Final summary of key insights of the pilot LCA.

The handprint analysis has been done for Pilot 3.1a and Pilot 3.3 and it follows the Carbon Handprint Rulebook (Pajula, et al., 2021).

In the last section of the deliverable the main general findings are summarised and the remaining gaps and questions are outlined for future research.

Main findings

- Printed electronics (i.e. additive manufacturing) show significant improvement potential over conventional printed circuit boards (PCBs) for many of the midpoint environmental indicators as defined in the EF3.1 methodology.
- For boards based on printed electronics, the metal inks for printing conducting layers are the key driver of environmental impacts, in particular silver-based inks. Alternatives like copper- and carbon-based inks show potential as an improvement, wherever technically applicable.

- These advantages are however limited by the relative contribution of the electronics of a product to its total environmental impacts. Across pilots, this tends to be higher for low-energy and small-form-factor devices.
- Reuse and longevity show a significant potential when looking at realistic use cases. Designing devices for reuse pays off even if the impacts per unit increase.
- An alternative wherever direct reuse is not possible is modularity, which can separate the strictly disposable elements from those that can be kept in use. This approach also shows significant improvements over benchmark.
- Material selection also shows to be an important aspect of eco-design. While substrate material has a limited impact, for bigger products the housing material selection is relevant. Furthermore, if low-impact electronics are technically feasible (e.g. carbon inks, paper substrates), other mechanical elements in the products become more environmentally relevant, making the material selection question an important one.
- While bio-based materials are promising, the use of recycled materials shows better results.
- Other opportunities across the life cycle have also been identified: light design can help reduce transportation impacts and decarbonisation of the supply chain can help tackling impacts related with more *off-the-shelf* components (e.g. ASIC chip).

Limitations and further research

- While observed as key element environmentally, there is still not much insight into the environmental aspects of conductive inks. Better understanding in this topic would help envision potential improvement routes (e.g. conductive inks based on recycled silver).
- Environmental data on bio-based and recycled materials is scarce. More availability would help researchers and companies in their material selection processes.
- Within SUSTRONICS some challenges in sorting printed and flexible electronics were identified but could not be studied extensively and thus could not be properly reflected in the LCA models. This could however prove relevant in terms of circularity and recovery of key materials and thus merits further investigation.

List of abbreviations

ABS	Acrylonitrile Butadiene Styrene
ADP	Abiotic resource depletion
AE	Accumulated Exceedance
AI	Artificial Intelligence
AM	Additive Manufacturing
ASIC	Application Specific Integrated Circuit
BLE	Bluetooth Low Energy
BM	Benchmark
BoM	Bill of Materials
CEM	Composite Epoxy Material
CFC	Chlorofluorocarbon
CTUe	Comparative Toxic Unit for ecosystems
CTUh	Comparative Toxic Unit for humans
EEG	Electroencephalogram
EF	Environmental Footprint
EoL	End of Life
GWP	Global Warming Potential
HOR	Hybrid Operating Room
IC	Integrated Circuit
IGTS	Image Guided Therapy System
IM	Injection Moulding
ISO	International Organisation for Standardization
LCA	Life Cycle Assessment
LCD	Liquid Crystal Display
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LDS	Laser Direct Structuring
LED	Light-Emitting Diode
LFS	Lateral Flow Strip
MJ	Megajoule
NFC	Near-Field Communication
ODP	Ozone Depletion Potential
PC	Polycarbonate
PCB	Printed Circuit Board
PCBA	Printed Circuit Board Assembly
PCR	Post-Consumer Recycled
PEF	Polyethylene furanoate
PET	Polyethylene terephthalate
PLA	Polylactic acid
PMMA	Poly(methyl methacrylate)
PoC	Point of Care
PWB	Printed Wiring Board

rABS	recycled ABS
RAM	Random-Access Memory
RGB	Red Green Blue
RU	Reusable
R2R	Roll-to-Roll
SDS	Safety Data Sheet
SMD	Surface-Mount Device
SU	Single-Use
SUS	Sustainable Single-Use
TDS	Technical Datasheet
TPU	Thermoplastic Polyurethane
TRL	Technology Readiness Level
UI	User Interface
WEEE	Waste of Electrical and Electronic Equipment
ZIF	Zero Insertion Force

Table of Contents

1. Introduction

1.1. Purpose of the document

This document presents the results of the Life Cycle Assessment (LCA) for all 10 pilots developed within Sustronics, as well as the results for the Handprint analysis performed for a selection of pilots (based on their appropriateness for such an analysis).

This deliverable covers the status of the pilots as of M34. While the development process is still in its finalisation phase (but ongoing), their status as reflected in this deliverable is deemed representative of their fully final stage. It is to be noted however, that in the time remaining until project closure changes in the pilots' designs are still possible.

1.2. Related documents

This deliverable is related to the following other reports:

- A more detailed and technical description of the pilots analysed in this deliverable can be found in D3.3 (for the second generations of the pilots).
- The final description of the pilots, including a summarised version of the final LCA results (including any necessary updates with respect to this deliverable) will be found in D3.4 (to be delivered).
- A broader overview of the eco-design process and how LCA has fit into the co-development work can be found in D4.5.
- The link between the LCA results and the prospective circular business models envisioned by the companies leading the pilots will be found in D4.7 (to be delivered).

2. Methodology

During Sustronics, Life Cycle Assessment has been used from the beginning to aid the pilots' work in considering and improving environmental sustainability during development as well as to generally assess, at a project level, the improvements that the developed technologies bring about. Therefore, the explicit goals of the LCAs presented in this document can be expressed as follows:

- Serving as a tool for the pilot work throughout the project to assess and benchmark the environmental performance of the various generations of the pilots.
- When reaching generation 3, assessing the final environmental impacts of the developed prototypes.
- Identify the pilots' environmental hotspots. These can point to future improvement potential but also give a picture of the environmental profile of printed electronics and their applications.
- Assess benefits and/or trade-offs with conventional solutions and track the sustainability targets of the pilots.

Due to the occasionally low technology readiness level (TRL) of the pilots and the explorative nature of the work done in SUSTRONICS, this document does not claim full compliance with ISOs 14040/14044 but does observe and follow them in the methodological application of LCA.

This document focuses on the latest generation (Gen 3) of the pilots as the baseline models for the LCAs. Further details on the previous iterations and the evolution of their impacts are given wherever deemed relevant or interesting. The scope of the LCAs is in all cases cradle-to-grave, in order to capture the broader picture and identify potential trade-offs. The focus will be placed however in different points of the full life cycle depending on the pilot's design and objectives. In general, special attention is paid to the production phase, given that all the prototypes are not yet in the market.

Table 1 below shows a scheme of the organisations responsible for the LCAs in each pilot. For practical reasons, each organisation has made use of the tools (LCA software and databases) that they had access to and therefore this aspect is not harmonised across pilots.

Table 1: Overview of organisations performing LCA and the tools used

Pilot #	Organisation performing the LCA	Used tools and databases
Pilot 1.1	Philips Electronics Nederland (PEN)	SimaPro Ecoinvent
Pilot 1.2	Philips Consumer Lifestyle (PCS)	Mobius Ecoinvent
Pilot 1.3	Fraunhofer Institut für Zuverlässigkeit und Mikrointegration (FHG)	Sphera LCA for Experts Sphera/Ecoinvent
Pilot 2.1	VTT Technical Research Centre of Finland Ltd (VTT)	Sulca[1] Ecoinvent
Pilot 2.2	VTT Technical Research Centre of Finland Ltd (VTT)	Sulca Ecoinvent

[1] Sulca - Semantum

Pilot 2.3	VTT Technical Research Centre of Finland Ltd (VTT)	Sulca Ecoinvent
Pilot 3.1a	Fraunhofer Institut für Zuverlässigkeit und Mikrointegration (FHG)	Sphera LCA for Experts Sphera/Ecoinvent
Pilot 3.1b	Fraunhofer Institut für Zuverlässigkeit und Mikrointegration (FHG)	Sphera LCA for Experts Sphera/Ecoinvent
Pilot 3.2	Fraunhofer Institut für Zuverlässigkeit und Mikrointegration (FHG)	Sphera LCA for Experts Sphera/Ecoinvent
Pilot 3.3	Infineon Technologies AG (IFAG)	OpenLCA Ecoinvent

All pilots use the EF3.1 methodology as the basis for the Life Cycle Impact Assessment (LCIA) phase. Each pilot however focuses on different indicators based mostly on data availability and relevance to the specific use cases. Table 2 shows a summary of the impact categories under EF3.1 as well as a brief explanation for each and its units, extracted from (Andreasi Bassi, et al., 2023). For further detail on the underlying LCIA methodologies, please refer to the source.

Table 2: EF3.1 midpoint indicator summary, as described by JRC

Impact category	Indicator	Unit
Climate change	Radiative forcing as Global Warming Potential (GWP100)	kg CO_2 eq.
Ozone depletion	Ozone Depletion Potential (ODP)	kg CFC-11 eq.
Human toxicity, cancer	Comparative Toxic Unit for humans (CTUh)	CTUh
Human toxicity, non-cancer	Comparative Toxic Unit for humans (CTUh)	CTUh
Particulate matter	Human health effects associated with exposure to PM2.5.	Disease incidences
Ionising radiation, human health	Human exposure efficiency relative to U^{235}	kBq U^{235}
Acidification	Accumulated Exceedance (AE)	mol H+ eq.
Eutrophication, terrestrial	Accumulated Exceedance (AE)	mol N eq.
Eutrophication, freshwater	Fraction of nutrients reaching freshwater end compartment (P)	kg P eq.

Eutrophication, marine	Fraction of nutrients reaching marine end compartment (N)	kg N eq.
Ecotoxicityicity, freshwater	Comparative Toxic Unit for ecosystems (CTUe)	CTUe
Land use	Soil quality index	Pt (*dimensionless*)
Water use	User deprivation potential (deprivation-weighted water consumption)	m^3 world eq.
Resource use, minerals and metals	Abiotic resource depletion (ADP ultimate reserves)	kg Sb eq.
Resource use, fossil	Abiotic resource depletion, fossil fuels (ADP – fossil)	MJ

Details on specific goals, system boundaries, allocation rules and data sources are presented per pilot in their corresponding sections.

These tool and methodological divergences across pilots mean that the results may not be directly comparable. In relative terms however, it can be seen that general trends and impacts distributions do largely converge, and it is on this basis that this document attempts to draw more general conclusions from the LCAs presented. The methodological differences however shall still be kept in mind when interpreting the conclusions.

This paper also provides a handprint analysis for selected pilots in Section 6. A carbon handprint analysis aims to estimate indirect benefits that a given product or system may have in another (for example, increased digitalization of a service may have impacts of its own but reduce the material needs elsewhere). While this principle does not apply to all pilots in the project, it is deemed appropriate for Pilots 3.1a and 3.3. Since no official standard exists, this document follows the guidelines defined in Carbon Handprint Guide (Pajula, et al., 2021).

The present document is divided in three parts. Firstly, the LCA results are presented for all pilots. This section also includes pilot specific details on system boundaries, LCA scope and data sources. For each pilot the full LCA results for the baseline model are presented, as well as a sensitivity analysis for a set of scenarios deemed relevant for each pilot. The second section presents the results for the carbon handprint for the selected pilots. Finally, the last section shows a set of final conclusions based on all the results and a set of guidelines for the future of printed electronics and the related research.

Table 3 shows a brief glossary of LCA-relevant terms and acronyms that will be used throughout the document.

Table 3: Brief glossary and acronym list for LCA-relevant terms used in the document

Term or acronym	Description
Life Cycle Assessment (LCA)	Method to quantitatively estimate the environmental impacts of a given product or service throughout part of or its entire life cycle.
Life Cycle Inventory (LCI)	List of all relevant material and energy inputs and outputs for a given product or service within the previously defined system boundaries. Serves as the basis model for the LCA.

Life Cycle Impact Assessment (LCIA)	Step of LCA that converts an LCI into a list of environmental impacts. It does so by applying characterisation factors, which use underlying mathematical and scientific models (also called LCIA methodologies) to convert relevant flows into a reference unit. For example: converting known direct greenhouse gas (GHG) emissions in a system into CO_2 equivalents.
Environmental impact indicator	A quantitative description of a certain effect in the environment e.g. climate change, water use…
LCA tool	Software dedicated to building LCI models and to calculate the resulting environmental impacts.
LCA database	Databases containing *ready-made* LCI models for materials, processes and components. These allow LCA practitioners (or any other user) to build LCI models of more complex products and services.
Cradle-to-gate	Refers to typical system boundaries for an LCA in where the process steps up to the *factory gates* are considered i.e. until the product is ready to ship.
Cradle-to-grave	Refers to typical system boundaries for an LCA in where the process steps up to the product's end of life are considered.
Production phase	Phase of the life cycle of a product which includes its manufacturing: from the extraction of the raw materials, through the production of the intermediate parts and components ending in the assembly of the final product. This may or may not include necessary transport and waste treatment during production, depending on available data and defined scope.
Transport phase	Phase of the life cycle of a product which includes the distribution of the product to consumers, retailers and/or stock centres.
Use phase	Phase of the life cycle of a product which includes the installation, usage and maintenance of the product.
End of Life (EoL)	Phase of the life cycle of a product which includes the disposal, recycling, treatment or even refurbishing of a product.
Bill of Materials (BoM)	List of parts and components in a product.
Allocation	Refers to the rules for which the environmental impacts of a broader system are attributed to its sub-products or sub-systems.

3. LCA results Case Study 1

3.1. Pilot 1.1

3.1.1. Introduction

In Pilot 1.1, Philips Medical Systems (PMS) and Philips Electronics Nederland (PEN) have the goal to minimize the environmental footprint of Philips' image guided therapy systems (IGTS), particularly the Azurion. The Azurion is an interventional X-ray system that is used in minimally invasive treatment. The pilot focuses on the development of a low-weight positioning and geometry concept, using the Philips Azurion platform as the reference benchmark case. The pilot addresses several of the main environmental impact drivers of large interventional X-ray systems: the extensive use of steel and aluminium in the gantry, ceiling support structures, energy usage, and packaging and transport.

Using LCA, the main environmental hotspots of the current Azurion system are assessed and compared to the environmental footprint of the new low-weight concept. Gen 3 of the Sustronics project is used for this LCA study.

3.1.2. Scope of the Study

This LCA is cradle-to-grave, meaning that it covers all relevant life cycle phases from raw materials acquisition to End-of-Life (EoL). The production phase is where Philips has the most control and where the lightweight geometry design has its most immediate effect, but the innovations in the concept also have effects further down the line, such as reduced transport emissions due to the lightweight design and the effect of an EcoMode in the use phase. Cradle-to-grave provides the end-to-end scope that can cover all these phases.

The Gen 3 model refers to the prototype of a lightweight geometry concept in its latest iteration, although different configurations are still possible and the design has not yet been optimized. The Azurion R3 with FlexArm is used as a benchmark, to compare the new concept to the state-of-the-art with comparable movement possibilities.

The study does not consider any particular cut-off rule, as all the Bill of Materials (BoM) data was available for the IGT device. No allocation rules were applied, as there were no by-product scenarios in the study.

For allocation at the conventional end of life, the study will follow the cut off approach for materials sent to the recycling facility (no credits will be provided for the recycling of products or energy produced from incineration).

As commented in the introduction, the EF3.1 methodology is used for the calculation of midpoint impact indicators. The report focuses on global warming as an environmental indicator.

3.1.3. Life Cycle Inventory

Benchmark

The Azurion R3 with FlexArm is used as a benchmark, to compare the new concept to the state-of-the-art. The BoM of this benchmark was available from the current design and production of the system. The system consists of:

- Ceiling mounted C-arm geometry with FlexArm, carrying the X-ray tube and a fixed D20 detector
- Patient table and UI's
- 58" LCD Monitor
- Processor Cabinets
- Packaging (wooden crate with metal frame to support the C-arm geometry)

Figure 1: Picture of the Azurion R3.

To provide a comprehensive impact overview of the system, the ceiling support structure was also included in the scope. This metal structure reinforces the ceiling so that it can support the weight and movement of the C-arm geometry. Its required strength and stiffness depend on the hospital building and can range from 500–2000 kg for a ceiling-mounted frame to 6000–8000 kg for a free-standing support frame. These two cases are therefore treated as separate scenarios in the sensitivity analysis. In the benchmark scenarios, an average ceiling mounted frame of 1250 kg is used.

The system is used in a Hybrid Operating Room (HOR). The key difference between a standard operating room and a HOR is the presence of an imaging system: in a standard OR, medical imaging devices are typically located in separate rooms, whereas in a HOR the X-ray system (for IGTS) is installed in the operating room. Energy use during the use phase is characterised by an ON mode (during scanning) and a standby mode (between patients and during idle periods). The working day is modelled as 12 hours and two benchmark scenarios are taken into account for the energy use: scenario 1 in which the user does not turn off the system at the end of the working day, and scenario 2 in which the user does turn off the system and display at the end of the working day (see Figure 3).

The system is not fully utilized for procedures during the 12 h working day. Clinical insights from the IGT business indicate 2-3 patients are treated per day on average in a HOR. (Patel, et al., 2020) report an average utilization rate of 43% for an HOR. For the benchmark case, the assumption is made that three patients are treated within the 12 h time window.

Gen 3 model | Lightweight geometry concept

The Gen 3 model is covering a new lightweight geometry concept. It differs from the benchmark on the following elements:

- The geometry carrying the X-ray tube and detector has been changed in design, leading to a reduction of approximately 650 kg in steel, aluminium and plastic.
- Due to the lightweight compact design, the packaging could be reconsidered, leading to a material reduction of approximately 550 kg in wood and steel.

- The Gen 3 concept features modular exchangeable detectors, so that the system can be optimized in use to a variety of different procedures. Three sizes of detectors are included in the concept, instead of only one detector in the benchmark.
- The utilization rate of the system can increase compared to the benchmark because the improved design is taking away adoption barriers for new procedures and the flexibility of the system is increased with the exchangeable detectors. The utilization is therefore modelled as different scenarios to see the effect, using the current utilization rate of 3 patients (43%), a realistic scenario of 4 patients (50-60%) and an optimistic scenario of 5 patients (70-80%) utilization.
- The ceiling support structure is also reduced in weight because of the lightweight concept. Since the structure needs to have a specific stiffness and needs to support not just the weight but also the accelerations of the system, the frame is calculated with a more conservative reduction of 50%, while the actual weight of the geometry hanging from the ceiling was reduced with 72%.
- The Gen 3 concept includes a Full EcoMode, which brings the system into energy saving mode in three ways:
    - The large display of the system will go into standby mode after a specific period of idle time.
    - The X-ray tube goes into standby mode when no patient is detected or when the staff indicates the system can go into standby via voice control.
    - The system has an automatic scheduled shutdown to deactivate the system during long periods of idle time (e.g. during the night, weekends).

This results in the following scenarios that will be calculated:

- Benchmark scenario 1:
    - Azurion R3 system
    - System and display are **not** turned off at the end of the working day
    - 3 patients treated per day
- Benchmark scenario 2:
    - Azurion R3 system
    - System is turned off and display to stand-by at the end of the working day
    - 3 patients treated per day
- Gen 3
    - Lightweight geometry concept with modular detectors
    - Full EcoMode:
        - System is turned off and display to stand-by at the end of the working day
        - X-ray tube and display are going into stand-by during idle time and between procedures.
    - Scenario 3A: 3 patients treated per day
    - Scenario 3B: 4 patients treated per day
    - Scenario 3C: 5 patients treated per day

The increase in utilization and the addition of the EcoMode can be visualized as follows in Figure 2, compared to the two benchmark scenarios.

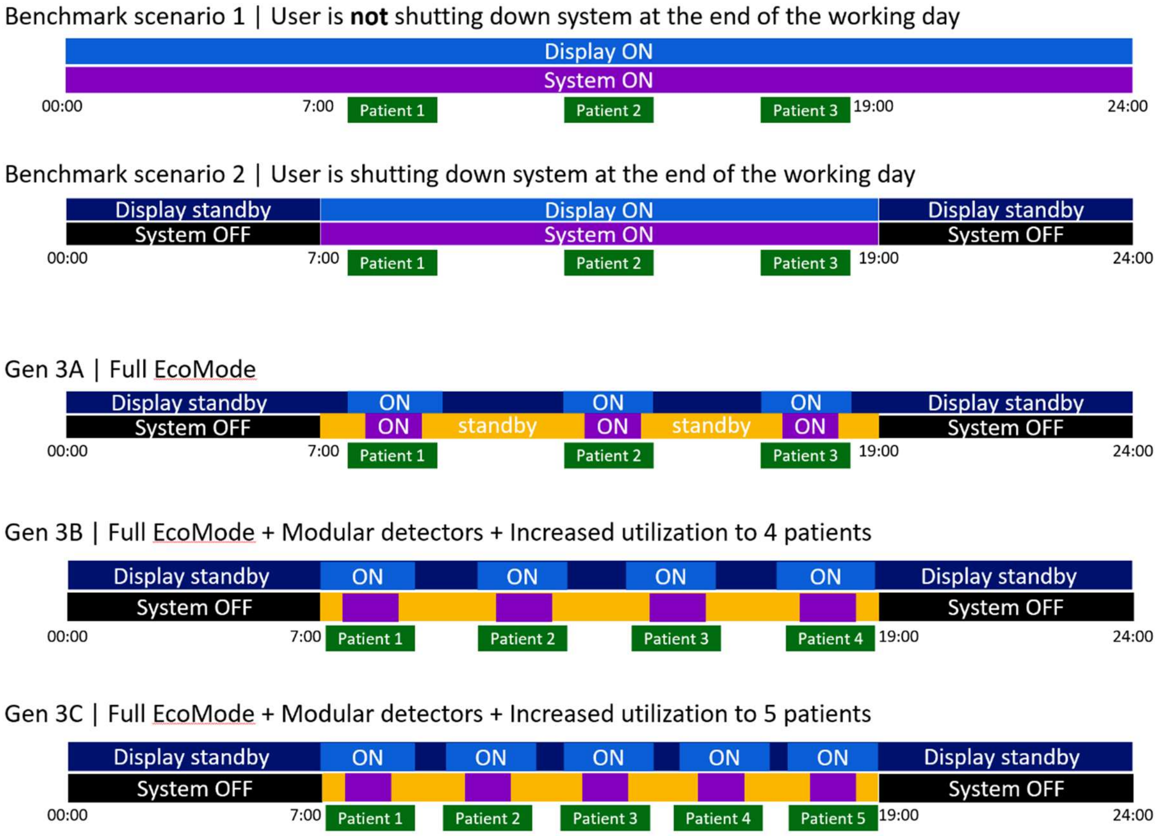


Figure 2: visual representation of the energy modes of the system and the display, and patients treated during a 24h day for the two benchmark scenarios, and the three Gen 3 scenarios including Full EcoMode, and the two higher utilization scenarios including the modular detectors.

A few elements are out of scope of the lightweight geometry concept and are therefore kept consistent between the benchmark and Gen 3 in the LCA comparison:

- The patient table and UI's
- 58" LCD Monitor (In terms of material. Gen 3 does include a standby mode during the use phase)
- Processor Cabinets

3.1.4. Life Cycle Impact Assessment

The Life Cycle Impact Assessment was performed using the Environmental Footprint (EF) 3.1 method. Results are presented for the Climate change indicator (kg CO_2 eq.) as Global Warming Potential (GWP) for the benchmark Azurion R3 configuration and the Gen 3 lightweight geometry concept, including the scenarios described in Section 2.1.3. The calculation aggregates impacts across the life cycle stages Manufacturing, Distribution, Installation, Use and End-of-Life (EoL). In addition, a use-intensity metric is calculated as GWP per patient, by dividing total life cycle GWP by the assumed lifetime utilisation (number of treated patients over lifetime) used in the scenario modelling. Table 4 summarises the results and Figure 3 gives a visual representation of the results.

Table 4: Climate change results by life cycle stage, by scenario, and GWP per patient.

Life Cycle Stage	GWP Impact (kg CO_2 eq.)				
	Benchmark Azurion R3		Gen 3 - Lightweight geometry concept		
	Benchmark scenario 01	Benchmark scenario 02	Gen 3A	Gen 3B	Gen 3C
Manufacturing	41324	41324	35007	36023	36023
Distribution	21559	21559	17003	17149	17149
Installation	129	129	129	129	129
Use	99419	61156	45341	47783	50225
EoL	455	455	306	332	332
Total	**162885**	**124623**	**97786**	**101416**	**103858**
% w.r.t Benchmark 01			-40%	-38%	-36%
% w.r.t Benchmark 02			-22%	-19%	-17%

Utilization per lifetime	7500	7500	7500	10000	12500
GWP Impact per patient	21,72	16,62	13,04	10,14	8,31
% w.r.t Benchmark 01			-40%	-53%	-62%
% w.r.t Benchmark 02			-22%	-39%	-50%

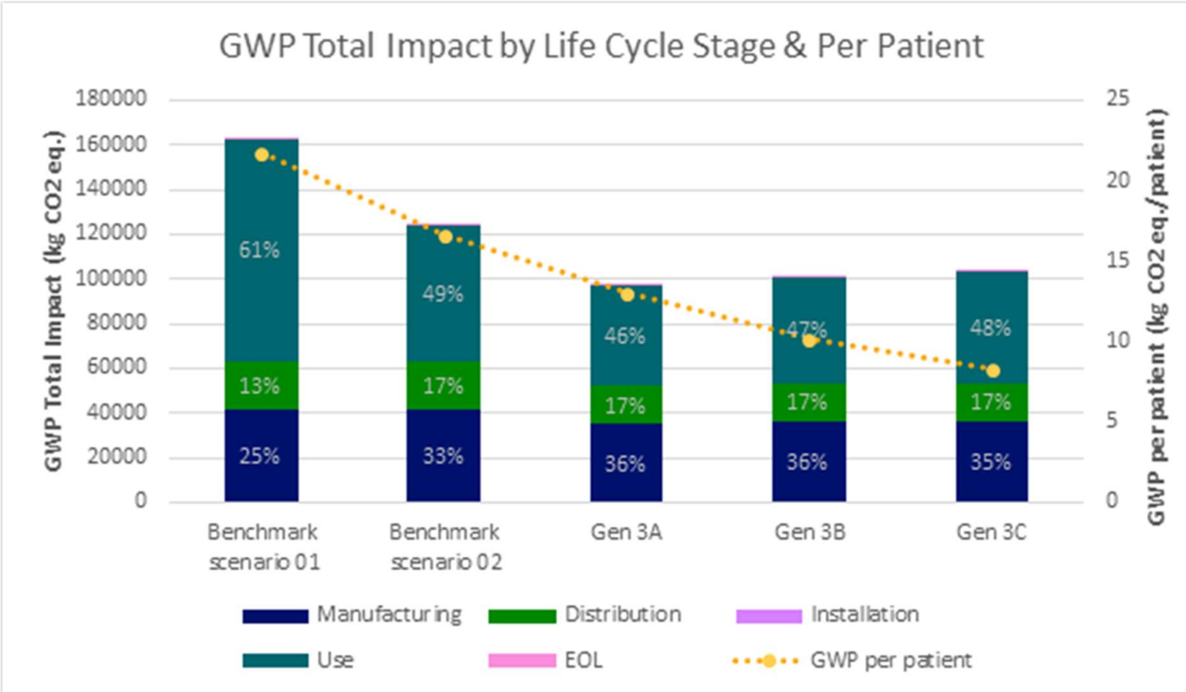


Figure 3: Climate change results by life cycle stage, by scenario, and GWP per patient. The percentages indicate the distribution of life cycle stage impact per scenario.

Across all scenarios, the Use phase is the dominant contributor to total climate change impact (46-61%), followed by Manufacturing (25-36%) and Distribution (13-17%). The Gen 3 concept reduces the absolute impacts of Manufacturing and Distribution relative to the benchmark scenarios due to the lightweight geometry and related packaging/transport changes, while the Use phase is reduced primarily through the EcoMode energy savings.

Relative performance vs. benchmark

The Gen 3 concept shows the following total Climate change reductions relative to the benchmark scenarios:

- **Relative to Benchmark scenario 01 (higher energy-use case):**
  - Gen 3A: **−40%**
  - Gen 3B: **−38%**
  - Gen 3C: **−36%**
- **Relative to Benchmark scenario 02 (lower energy-use case):**
  - Gen 3A: **−22%**
  - Gen 3B: **−19%**
  - Gen 3C: **−17%**

These results underline the importance of use-phase assumptions (and user behaviour) in the benchmark definition: the achievable relative improvement depends strongly on whether the reference system is assumed to be turned off outside operating hours.

Climate change intensity per patient

While Gen 3B and Gen 3C have slightly higher absolute life cycle impacts than Gen 3A due to higher energy use for more procedures, the increased lifetime utilisation leads to substantially lower impact per treated patient. Compared to the benchmark scenarios, the reduction is as follows:

- **Relative to Benchmark scenario 01 (higher energy-use case):**
  - Gen 3A: **−40%**
  - Gen 3B: **−53%**
  - Gen 3C: **−62%**
- **Relative to Benchmark scenario 02 (lower energy-use case):**
  - Gen 3A: **−22%**
  - Gen 3B: **−39%**
  - Gen 3C: **−50%**

These results underline the importance of considering not only the absolute product environmental footprint, but also the impact per patient, as changes in utilisation can significantly influence the interpreted environmental performance of the system.

Full comparison on impact indicators

Figure 4 below shows the comparison of the Gen 3A model with Benchmark 02, to determine the change for different impact categories. Overall, the reduction in all categories is between 12-22%, with the biggest improvements (>20%) in the categories Climate change, Eutrophication-terrestrial, Land use, Photochemical ozone formation, Resource use, and Water use.

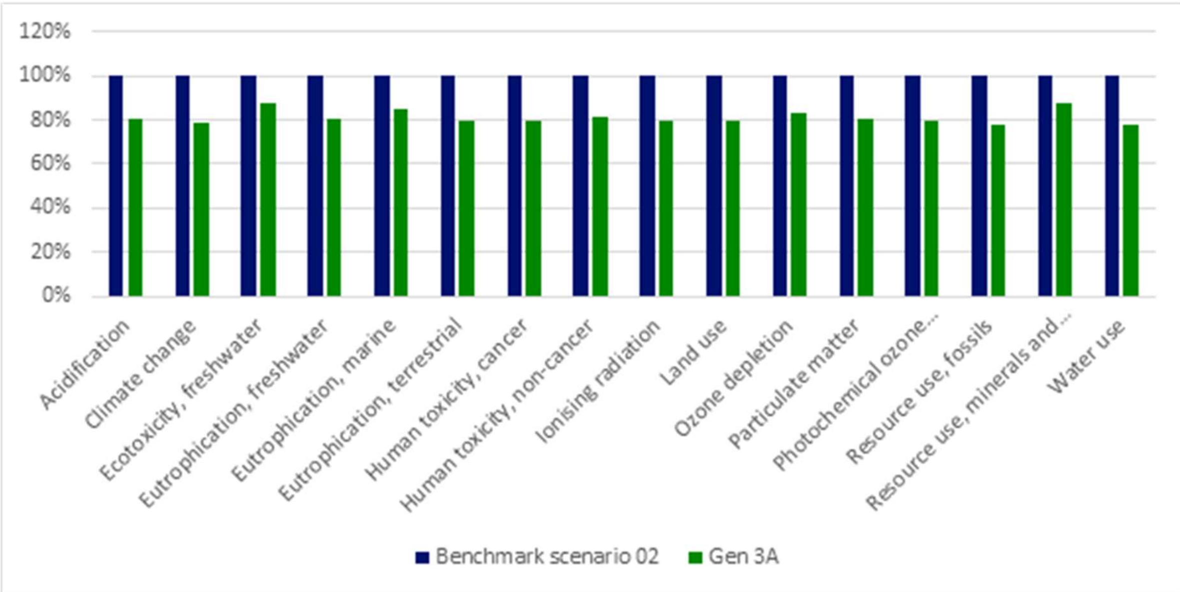


Figure 4: Comparison of Benchmark scenario 02 to the Gen 3A model on several impact categories.

3.1.5. Life Cycle interpretation and scenario analysis

The use and context of the system can vary between one hospital to another and one user to the next. Therefore, two different benchmark scenarios and three different utilization rates have already been included in the analysis. One additional aspect that can shift the results and the hotspots in the LCA is the room and building context the IGT system is placed in. Some hospitals are constructed such that the walls and ceilings can carry heavy loads, which means the IGT system can be mounted with a relatively simple support structure to the ceiling. However, in a worst-case situation the ceiling is not suitable to hold the weight, which means a robust free-standing frame needs to be built to carry the weight and forces of the imaging system. This can shift the material footprint, from a ceiling mounted frame of 500-2000 kg, up to the worst-case situation with a free-standing frame of 6000-8000 kg. The following weights are used in the calculation:

- Benchmark Azurion R3
  - Average ceiling mounted frame of 1250 kg
  - Worst case free-standing frame of 7000 kg
- Gen 3A lightweight geometry concept
  - Average ceiling mounted frame of 650 kg
  - Worst case free-standing frame of 3500 kg

The influence of this support structure was calculated in the scenarios below with the results displayed in Table 5 and Figure 5.

Table 5: Climate change results by life cycle stage, comparing the average ceiling mounted support frame to the worst-case free-standing support frame

Life Cycle Stage	GWP Impact (kg CO_2 eq.)			
	Azurion R3 Benchmark Scenario 02		Gen 3A lightweight geometry concept	
	Average Case	Worst Case	Average Case	Worst Case
Manufacturing	41324	67078	35007	47884
Distribution	21559	22597	17003	17522
Installation	129	129	129	129
Use	61156	61156	45341	45341
EoL	455	524	306	341
Total	124623	151484	97786	111216
% w.r.t to Average Case		+22%		+14%
% w.r.t to Benchmark			-22%	-27%

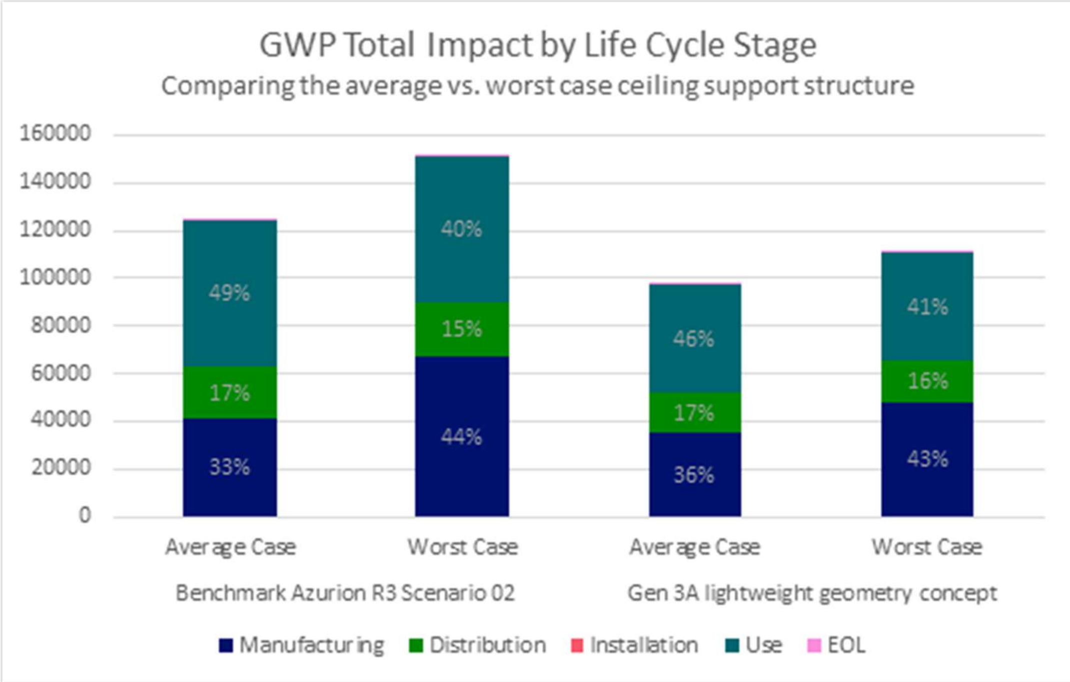


Figure 5: Climate change results by life cycle stage, comparing the average ceiling mounted support frame to the worst-case free-standing support frame.

The worst-case scenarios with a free-standing support frame are 14% and 22% higher in total environmental footprint, compared to the average ceiling mounted frame. This is mainly due to the increase in impact of the Manufacturing phase, increasing from 33-36% to 43-44% of the total footprint. The Use phase impact is not increasing since the support structure has no effect on the energy use. In the worst-case scenario, the Manufacturing phase even becomes slightly higher in impact than the Use phase. The Distribution phase also increases, but relatively little since local production and truck transport has been taken into the calculation for the metal beams of the frame.

3.1.6. Conclusions

The LCA results show that the climate change impact of the Azurion R3 system is dominated by the use phase in all assessed scenarios, with manufacturing and distribution as the next most relevant contributors. The Gen 3 lightweight geometry concept reduces climate change impacts across the full life cycle by combining (i) reduced material demand in the geometry concept and associated packaging, lowering Manufacturing and Distribution impacts, and (ii) reduced operational energy demand through Full EcoMode, lowering Use-phase impacts. As a result, the Gen 3 concept consistently outperforms the benchmark under both benchmark energy-use assumptions.

- Total life cycle climate change impact is reduced from **162,885 kg CO_2 eq.** (Benchmark scenario 01) and **124,623 kg CO_2 eq.** (Benchmark scenario 02) to **97,786–103,858 kg CO_2 eq.** for Gen 3 (scenarios 3A–3C), corresponding to a reduction of **36–40%** vs. Benchmark 01 and **17–22%** vs. Benchmark 02. The reduction in the broader list of impact categories ranges from **12-22%** when comparing Benchmark 02 to Gen 3A.
- On a per-patient basis, the climate change intensity decreases from **22.81 kg CO_2 eq./patient** (Benchmark 01) and **17.71 kg CO_2 eq./patient** (Benchmark 02) to **13.59** (Gen 3A), **10.55** (Gen 3B) and **8.64 kg CO_2 eq./patient** (Gen 3C), demonstrating that increased utilisation can substantially improve the interpreted environmental performance.

- The sensitivity analysis on the support structure highlights that the installation context can materially influence results: moving from an average ceiling-mounted frame to a worst-case free-standing frame increases total climate change impacts by approximately **14%** (Gen 3A) and **22%** (Benchmark scenario 02), mainly through higher Manufacturing impacts.
- Finally, the comparison between benchmark scenarios confirms that user behaviour and system operating modes (e.g. switching off outside operating hours) have a strong influence on the reference footprint and therefore on the magnitude of the achievable relative improvements.

3.2. Pilot 1.2

3.2.1. Introduction

In Pilot 1.2, Philips Consumer Lifestyle (PCL) focuses on reducing the environmental footprint of Grooming & Beauty (G&B) devices. Previous LCAs have shown that printed circuit board assemblies (PCBAs) are significant contributors to the total impact of these devices.

This Pilot explores how alternative technologies can reduce these impacts and provide insights for future electronic and product innovations.

Below is an overview describing the aims of each Generation:

<u>Generation 1 – Learn</u>
Identification of environmental hotspots and refinement of the LCA methodology.

<u>Generation 2 – Fast Iteration & Test</u>
Application of insights from Generation 1 to a simple PCBA and an assessment of environmental improvement potential of new selected technologies.

<u>Generation 3 – Integration</u>
Integration of the improved technologies into a more complex PCBA and evaluation of effect on the environmental impact at both PCBA Level and Total Product Level.

This deliverable reports specifically on Generation 3 with a high-level overview of LCA results. Due to confidentiality reasons the details are left out of the document and are only presented in non-public deliverables.

3.2.2. Scope of the Study

The following LCAs were conducted for Gen 3:

PCBA Level: (cradle-to-gate)

a) Baseline PCBA
b) Gen 3 PCBA

Product Level: (cradle-to-grave)

c) Baseline product (i.e. product + Baseline PCBA)
d) Gen 3 product (i.e. product + Gen 3 PCBA)

For the PCBA Level LCAs, the scope is cradle-to-gate. The proposed new PCBA technologies have effect on the Production phase of the PCBAs only. For the Use Phase, the impact is expected to remain similar between Baseline and Gen 3.

For the End-of-Life Phase, there is no accurate data available for both the Baseline as well as for Gen 3. As the impact was expected to be relatively low, it was not considered within scope of the study. Hence, for the PCBA Level study, the scope is cradle-to-gate. The functional unit is defined as “per PCBA”. This was done because the Baseline and Gen 3 PCBAs have different weights.

For the Product Level LCA, the scope is cradle-to-grave. The functional unit is defined as “to perform grooming activities using a device over a lifetime of X years”. Due to confidentiality reasons the lifetime is left out of the document. The supply chain logistics were excluded from the scope of the study. This is because the impact of upstream and downstream transport is very similar for both cases and has minimal impact on the overall scope.

For End-of-Life, a 70% recycling and a 30% incineration rate was considered for the total device for both the Baseline and Gen 3. This was based on the estimated industry average recycling rate for a typical low-end hand-held appliance. Although not accurate, the accuracy of the recycling rate data is of relatively low importance to the total LCA.

This study does not consider any particular cut-off rule, as all the BoM data was available for PCBA and the appliance under study. There were no allocation rules applied, as there were no by-product scenarios in the study.

For estimating environmental impacts, EF3.1 methodology was adopted with midpoint indicators.

For reasons of confidentiality – only a high-level overview of the Results will be shared.

3.2.3. Life Cycle Inventory

Baseline PCBA

The Baseline PCBA is a single-sided PCBA. The key data source for the part weights and type originate from available eBoM data. Supplier data was also used for many electronic components – however where that was not obtainable the components were physically weighed.

The exact primary data is confidential and will not be shared in this deliverable. The component and material types were matched with relevant datasets from the EcoInvent v3.11 database.

Gen 3 PCBA

Three alternative technologies were introduced to reduce the environmental impact of the Baseline PCBA. All part masses and compositions were supplied or measured in collaboration with TNO Holst Centre. The exact primary data is confidential and will not be shared in this deliverable. Similar to the Baseline, the part and material types were matched with relevant datasets from the EcoInvent v3.11 database.

3.2.4. Life Cycle Impact Assessment

This section presents high-level the key LCA results: the environmental impact reduction at a PCBA Level, followed by the corresponding reduction at a Product Level. Due to confidentiality reasons the details are left out of the document and are only presented in non-public deliverables.

Carbon footprint reduction due to design changes (PCBA Level)

The Gen 3 PCBA achieved the PCBA Level target. This reduction is predominantly driven by one of the alternative technologies. The two other alternative changes have significant reduction on Part Level, but the impact on PCBA Level is negligible.

Carbon footprint reduction due to design changes (Product Level)

On Product Level, integration of the Gen 3 PCBA resulted in a significant impact reduction. However, it was not sufficient to meet the target.

3.2.5. Life Cycle interpretation and scenario analysis

Two additional approaches to further reduce the impact on a Product Level were evaluated. They show promise to further reduce environmental impact on a Product Level. Due to confidentiality reasons the details are left out of the document and are only presented in non-public deliverables.

3.2.6. Conclusions

In conclusion, the new more detailed LCA method delivered a more accurate PCBA impact assessment than the default LCA method, and is therefore well suited for cases where sufficient time is available and the need for detailed PCBA Level LCA results exist.

All three alternative technologies show clear potential. However, their effectiveness at PCBA and Product Level is strongly dependant on their relative contribution to the overall Baseline design.

For this specific PCBA studied, one of the alternative technologies was the dominant driver for improvement. Together the combined contributions resulted in meeting environmental impact reduction KPI target on a PCBA Level. However, on a Product Level, the current proposed changes did not meet the target. More work is needed to understand the effect of the other intended circular strategies.

3.3. Pilot 1.3

3.3.1. Introduction

Pilot 1.3 is part of the *Circular Electronic Devices* use case and aims to develop a sustainable luminaire. It is led by Signify with contributions from TNO, VTT, SCR, UPM, ARNP, TER, FHG, and MIR. It focuses on the following eco-design principles:

- Printed LED strips that reduce both energy and material use when compared with conventional PCB-based LED strips.
- Housing material with reduced environmental impact.
- Modular design for easy disassembly, allowing for easier reuse of parts and materials separation.

Using LCA, the main environmental hotspots of the current prototype are assessed and its benefits compared to conventional luminaires is estimated.

3.3.2. Scope of the Study

This LCA is cradle-to-grave, meaning that it covers all relevant life cycle phases from raw materials acquisition to End-of-Life (EoL). The main focus of the analysis however lays on the production phase, since it’s the phase that Signify has the most control over and where the luminaire’s design has its most immediate effect. The scope was set at cradle-to-grave however in order to better capture impacts and trade-offs further down the line.

The baseline LCA model refers to a configuration that better reflects the prototype in its latest iteration, although different configurations (e.g. in terms of housing materials) are still possible. With the help of Signify, a reference model reflecting more state-of-the-art luminaires has also been modelled for benchmarking purposes.

In this LCA no particular cut-off rule has been followed, and the main inclusion criteria has been data availability. A more detailed explanation of the included processes is given in the following section.

The EoL allocation approach chosen has been 0/100, not including credits for avoided production of the recycled elements.

As commented in the introduction, the EF3.1 methodology is used for the calculation of midpoint impact indicators. In the report only selected indicators will be analysed in depth.

3.3.3. Life Cycle Inventory

Baseline model

The sustainable luminaire developed in Sustronics is composed by the following parts: housing, diffusor, downward lighting and upward lighting.

The housing is composed of a mix of materials based on bio-plastics and cellulose. In order to reduce material use, different versions of the housing have been tested with different levels of infill. For the baseline model the lowest infill approved has been used i.e. a 25% infill version of the housing. The part is manufactured via 3D printing. Data on the amount of material used is provided by Signify, as well as the recipe. The 3D printing energy requirements are estimated based on several sources ranging from literature (Ulkir, 2023) to specialized websites[2]. While primary data on the printing was not available, the estimated value has been consistently reached based on different datapoints. See Figure 6.

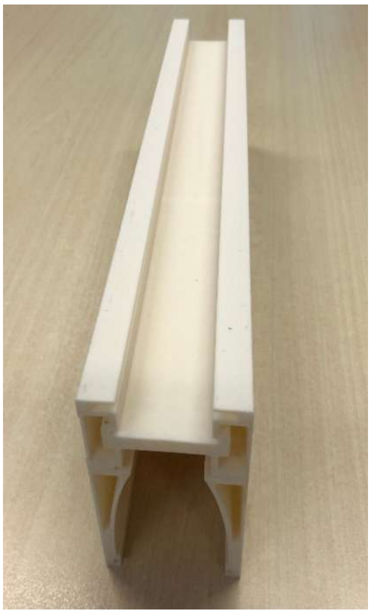


Figure 6: Picture of the 3D printed luminaire housing.

The diffusor is a mechanical piece that ensures proper distribution of the light from the LED strips outwards. It is manufactured by VTT mixing layers of plastic, cellulose and binder. The full recipe as well as the main processing parameters for the modelling have been provided by VTT.

The downward lighting is a LED strip based on printed electronics (i.e. manufactured using R2R printing). The substrate is a PC film with silver conductive tracks printed on top, as well as cover layers for protection and underfill for rigidity. The downward lighting uses 73 surface mounted LEDs and conventional board-to-board connectors. The Bill of Materials (BoM) was provided by Signify while the printing process data (mainly the electricity use per step) was provided by Holst Center.

The upward lighting is modelled similarly to the downward lighting with minor differences: it uses 90% recycled PET as substrate and 36 coloured LEDs instead of the 60 white LEDs of the downward lighting. Lastly, the upward lighting also has some passive components (resistors and signal diodes).

At this stage and due to the modular and detachable design of the luminaire, overall assembly of the device is assumed to be manually achieved and thus it carries no additional impacts in the model.

Transport covers upstream transport (i.e. transport of parts to assembly), based on the current locations of the partners and the sent part weights. Since currently the products are not in the

[2] See for example nominal power in https://store.heygears.com/blogs/blog/how-much-electricity-does-a-3d-printer-use?srsltid=AfmBOorJXvNlXFDM3_RouxfV1cwsLXBNiMYRnZ6kk0863ONzxL_Q5B-U and printing process parameters in https://www.raise3d.com/de/blog/how-long-does-3d-printing-take/

market, no transport to consumer is included. This phase should therefore be considered as provisional modelling and not yet representative of a real-life scenario.

Use phase is modelled based on data provided by Signify. For all models the same fixed flux (lm) output is assumed and the power consumption (W) for each is derived based on their efficacy (lm/W). Lifespan is assumed to be 50,000 h for all models.

The luminaire is assumed to be properly sorted into WEEE, as it is covered in a particular group within the WEEE regulation[3] and it is not easily disposable in the mixed waste. Given the modularity of the design, efficient separation of housing and electronics is assumed. Housing is assumed to go to incineration while the electronics part is assumed to go on to smelting-based metal recovery (see Umicore process). EoL collection and transport data is based on (Haupt, Kägi, & Hellweg, 2018).

The model has been built using Sphera LCA for Experts as the base software. The background data has been pulled from the Sphera and Ecoinvent databases (Sphera being the preferred option with Ecoinvent used whenever data gaps in Sphera existed). Importantly, the conductive silver ink has been modelled using the Ecoinvent dataset for metallization paste[4] as reference, rebuilt using Sphera datasets.

Benchmark

In order to estimate the benefits of the developed prototype over a more conventional luminaire, a reference model was built. The BoM for this benchmark model was developed alongside Signify based on their portfolio (Signify Holding, 2023) The reference model differs from the Sustronics model in the following elements:

- The housing is made of aluminium. Assumed to be primary aluminium, modelled using Sphera datasets. Part production assumed as aluminium die casting.
- The diffusor is made out of fossil based PMMA instead of bio-based materials.
- LED strips are identical but instead of additive manufacturing, components are mounted over a 1-layer rigid PCB, manufactured using conventional etching-based subtractive techniques.
- Minor changes are applied on transport, use phase and EoL models in order to adapt them to the reference luminaire (changes in weight, material composition, etc.).

3.3.4. Life Cycle Impact Assessment and scenario analysis

Figure 7 below shows the full life cycle impacts of the Sustronics prototype for a selected list of impact categories. Since the lifespan of a luminaire is very long, the full life cycle impacts are dominated by the use phase; the only exception being mineral and metal use which has its hotspot in the production phase. Transport and EoL show a minimal contribution in comparison.

[3] https://environment.ec.europa.eu/topics/waste-and-recycling/waste-electrical-and-electronic-equipment-weee_en

[4] https://ecoquery.ecoinvent.org/3.12/cutoff/dataset/2180/documentation

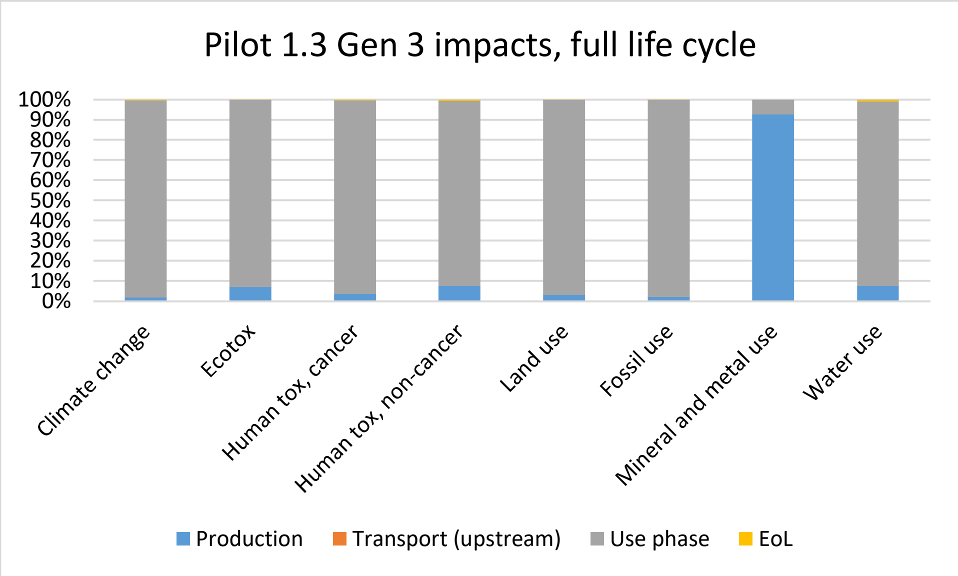


Figure 7: Full life cycle impacts distribution for the sustainable luminaire, broken down per life cycle phase.

Figure 8 shows the impacts distribution for the manufacturing phase of the luminaire, divided per parts. For most indicators, the housing is the main driver of the impacts. In this case we are looking at a comparatively bulky part and, according to literature (see previous section), the energy use of 3D printing can be relatively high (between 1 and 4 kWh for the lowest infill housing version). Both LED strips show different contributions depending on the indicator. They generally show a contribution ranging from 10% to 30% with the exception of non-carcinogen human toxicity and mineral and metal use, where they combine to represent 80% to almost 100% of the impact.

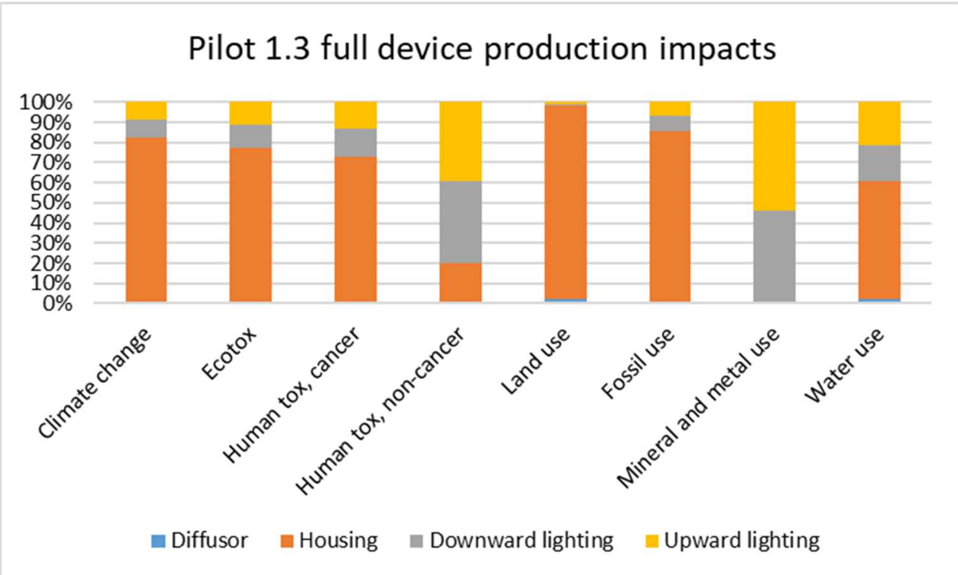


Figure 8: Sustainable luminaire production impact share, divided by parts.

Figure 9 below shows the impact distribution of the downward lighting as the example of the LED strips environmental impacts. As it can be seen, the silver conductive ink is the main driver for all categories under analysis, usually contributing 70% or above.

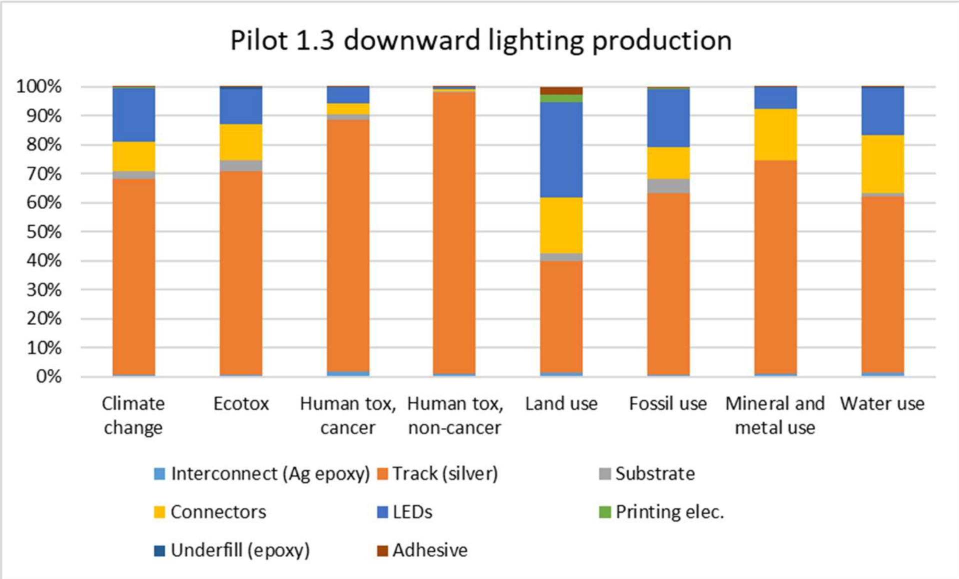


Figure 9: Downward lighting module production impact share, divided by component group.

From the contribution analysis it can be seen that overall, the housing production and the conductive ink used in the LED strips are driving all production impacts. At a full life scale however, the use phase dominates the environmental performance of the device due to its long lifespan.

Comparison to reference

In order to compare the sustainable and reference luminaires, the production impacts of both models are analysed for a selected list of key impacts: climate change, mineral resource use and ecotoxicityicity.

Figure 10 below shows the climate change comparison. The Sustronics model shows almost a 50% drop in the production emissions. The bio-material based housing, alongside the material reduction due to the semi-hollow design allowed by 3D printing brings about the biggest reduction in comparison with the heavier aluminium housing. Furthermore, the printed electronics-based LED strips also show an impact roughly half of that of the conventional PCB LED strip. Lastly, the new diffusor also has a lower impact than the reference, although its low contribution makes the difference less relevant.

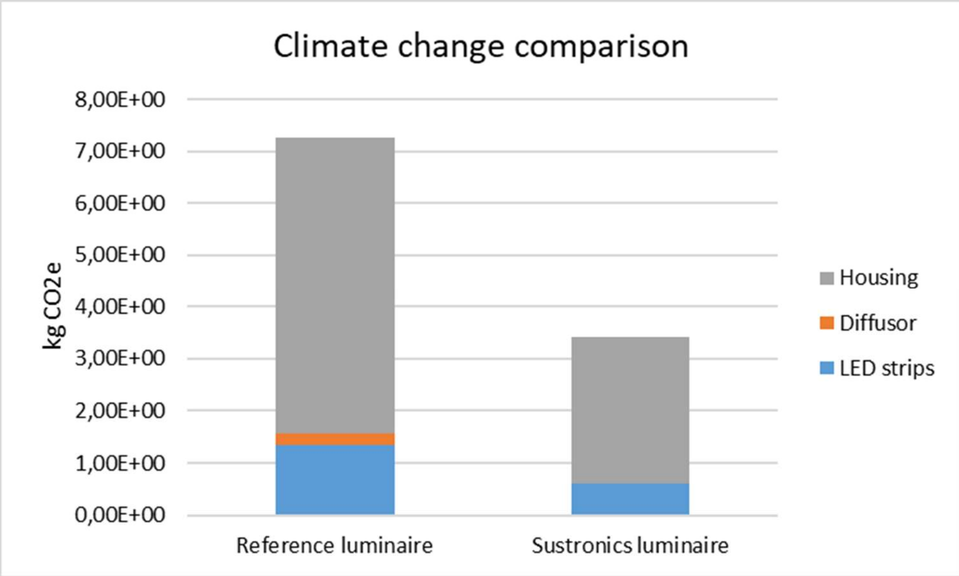


Figure 10: Comparison of the reference and sustainable luminaire production impact, for the indicator climate change (following the EF3.1 categories).

At the electronics level, silver conductive inks are the clear environmental hotspot for printed electronics (Naji Nassajfar, 2023) and therefore show potential for further improvement by replacing these with other ink formulations (e.g. copper inks) or even by inks made out of secondary silver. Figure 11 below shows a comparison of the production impacts for the current, silver ink version of the luminaire and a version employing copper ink for the LED strips instead of silver. The LED strips together show a climate change reduction of 65% and an overall drop of 11% (production level). This effect is higher in indicators like mineral resource use where the use of minerals like silver is more critical. A full model of recycled silver is not available but based on data from (Cespi, et al., 2025) it can be estimated that the production of secondary silver could entail up to 92% lower emissions than production of virgin silver (a similar dimension could be expected for mineral resources use, since this indicator is connected to extraction of materials). This would mean around 60% impact reduction at LED strip level.

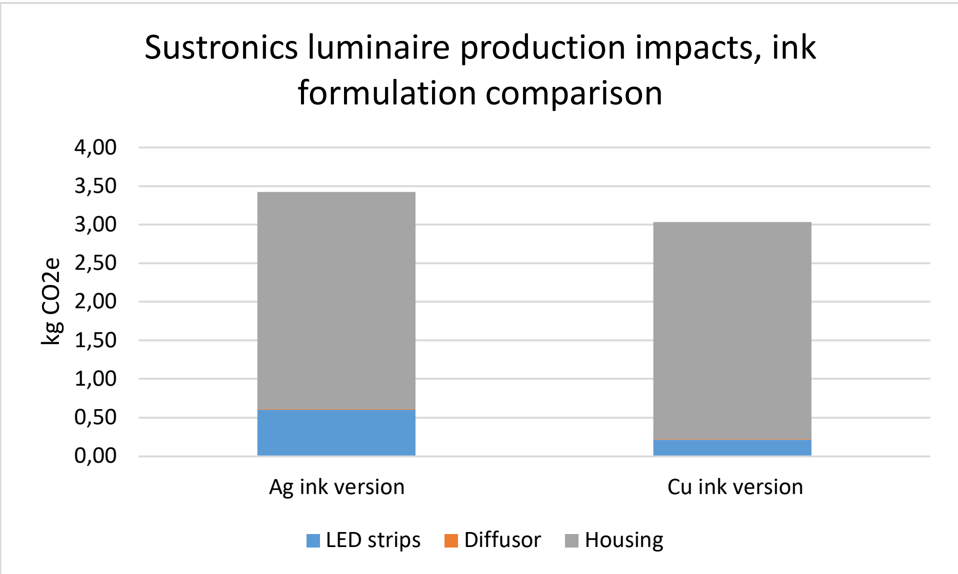


Figure 11: Comparison of the current Sustronics luminaire (using silver conductive ink for both downward and upward light LED strips) and a version of the devices substituting that for copper ink.

A similar picture can be seen in other indicators like ecotoxicityicity, see Figure 12. Here the Sustronics model also shows a reduction, although more modest than that for climate change. Bio-plastics are known to have relatively high ecotoxicityicity impacts linked with the feedstock production early in their supply chain (Chen, Pelton, & Smith, 2016) and thus the reduction here is mostly attributable to the lower material use due to the housing design. The lower material use and electricity needs for the printed LED strip also shows a reduction.

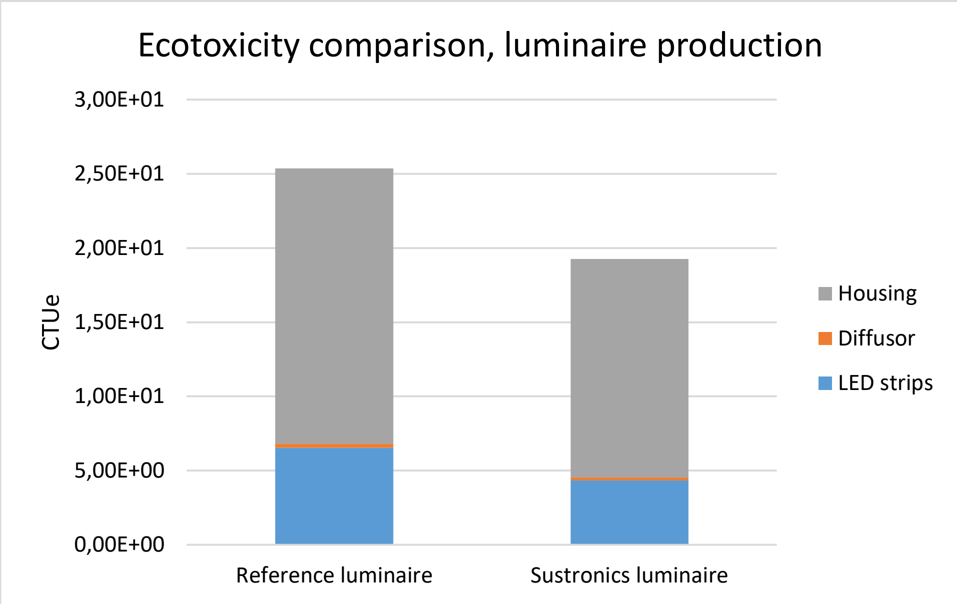


Figure 12: Comparison of the reference and sustainable luminaire production impact, for the indicator ecotoxicityicity (following the EF3.1 categories).

3.3.5. Conclusions

The luminaire developed in Sustronics shows reductions in most environmental impacts. This is achieved by two key changes in design:

- Low impact and material-efficient design that allows for a lighter but still serviceable housing that brings about most of the impact reductions.
- Additive manufacturing of LED strips that reduces both the material and the energy needed to produce the electronics of the luminaire.

Further improvement potential remains on both elements, however:

- The housing is still the main contributor for most impacts both due to the material related impacts as well as the processing (3D printing). Regarding the printing, better data would help better assess the extent of its contribution. Regarding the material, potential alternatives like recycled (bio-)plastics could be studied or, even more interesting, making use of the highly modular design to directly reuse the housing part.
- The most environmentally relevant part of the electronics side is the silver conductive ink. Looking into alternative inks is therefore recommended, for example copper-based inks that could be functional for this application.

4. LCA results Case Study 2

4.1. Pilot 2.1

4.1.1. Introduction

Pilot 2.1 is part of the *Sustainable manufacturing for electronics* use case and aims to develop a next-generation EEG (Electroencephalogram) monitoring solution combining embedded electronics with sustainable design principles. The objective is to reduce the environmental footprint of EEG systems while maintaining clinical-grade signal quality and usability. The pilot is led by PLUX with contributions from SCR, PIEP and VTT. The pilot emphasizes using eco-friendly materials and integrating energy-efficient designs in healthcare monitoring equipment. This is achieved by creating EEG electrodes and sensor designs that are environmentally sustainable, minimizing disposable materials and lowering environmental footprint, ensuring signal quality matches or surpasses current clinical standards. Life Cycle Assessment is used to identify the key environmental impacts of the current prototype.

4.1.2. Scope of the Study

Scope of the study is cradle-to-grave with especial focus on cradle to gate for the electrode and sensor as those are the steps that the pilot partners have control over. Use stage is based on estimations by project partners and end of life is also an estimate based on literature and assumed treatment routes.

The baseline LCA model represents the configuration corresponding to the prototype of generation 3. The use case consists of a two-channel forehead EEG system for daily-use scenarios, where printed electrodes connect to a sensor and signal hardware. The pilot activities have progressed well: the electrode solution is mature, but sensor development remains at the prototype stage. A first working prototype exists, with system-level validation underway. As a result, the LCA for the sensor reflects its current state rather than the final product. With one month left in the project, further improvements are anticipated.

As with the pilots in case study 1, no specific cut-off rules were applied in this LCA; data availability served as the primary inclusion criterion. Further details regarding the included processes are outlined in the subsequent section. The selected EoL allocation approach is 0/100, which incorporates credits for the avoided production of recycled components. These credits are presented separately to maintain clarity.

EF3.1 methodology was used for calculating midpoint impact indicators. The report focuses on a selected list of relevant indicators but presents all 16 environmental impact categories.

4.1.3. Life Cycle Inventory

Baseline model

The baseline model for embedded electronics has the following parts: biosignalsplux 8-channel hub, Bluetooth dongle, EEG sensors and EEG Electrodes. The configuration also uses OpenSignals software to visualize the data and Python script to analyse the data. This assessment focuses only on the EEG sensor and electrodes as other parts of the system are not under development in the project.

The sensor is developed by PIEP, and it's made by laser direct structuring (LDS) technology. There are four steps to making the sensor: polymeric part processing, laser structuring, metallization and components assembly. Primary data about the sensor manufacturing was provided by PIEP. The polymeric part is made from polycarbonate (PC), the production of which is modelled using ecoinvent database. The sensor can be used for multiple measurement cycles.

The electrode is single use and developed by SCR and comprises of multiple materials and layers. The basis is a paper substrate onto which conductive traces are printed using conductive copper ink. Hydrogel and skin adhesives are used for additional properties. There is also a paper based protective liner, an aluminium-lined protective bag and stainless-steel snap buttons included in the configuration. More details on performance of the materials and processes are reported in WP1 deliverables D1.4 (Sustainable materials and their characteristics, M18), D1.5 (Sustainable processes and their characteristics, D1.5) and D1.6 (Material and process validation and testing results, M24).

Primary data on copper ink production was not available, so product technical data sheets (TDS) and safety data sheets (SDS) were used instead to estimate its composition. As the ink production process requires energy as well as chemicals, and the energy amounts were not available, an estimation was needed. For that reason, ecoinvent process *metallization paste production, front side*, was used. It models the average production of metallization paste based on data for solder production and the chemical composition of average pastes. The underlying data is from 2006 and thus quite old, but under the circumstances it was the best available. The process includes inputs for factory infrastructure, organic chemicals, lead, silver, heat, and electricity. To utilize the energy inputs from this dataset, lead, silver and organic chemicals were removed and replaced with the chemicals of copper ink.

Use phase is modelled based on data provided by SCR and PLUX. The biosignalsplux hub uses a small Li-ion battery as its power source which can last up-to 5000 hours. One measurement cycle is set to 10 h and uses two electrodes and one sensor.

The electrode and sensor are assumed to be properly sorted into WEEE and medical waste fractions respectively while the li-ion battery is sent to WEEE treatment. Given the modularity of the design, efficient separation of sensor, electrode and battery is assumed. Electrode is assumed to go to medical waste treatment using steam sterilization, followed by incineration, while the WEEE fractions are assumed to go to shredding and ultimately smelting-based metal recovery and plastic recycling.

The model has been built using Sulca LCA tool as software. The background data has been pulled from the Ecoinvent 3.11 database.

Benchmark

The clinical gold standard electrode, a PET-based hydrogel electrode, was considered as benchmark. LCI data for this electrode was not available, so generation 1 electrode from Pilot 2.1 using fossil-based PET and hydrogel was chosen. For the sensor electronics, a traditional PCB was used to see how replacing PCBs with printed electronics impacts the devices environmental impacts.

In the Ecoinvent database, there are multiple different datasets for PCBs, or printed wiring boards (PWB) as they are called there. For this application a process called *printed wiring board production, mounted mainboard, mobile device, double-sided, Pb free* was chosen. This process contains the mounting of components on the PWB. Production of the components is also included through the respective datasets. The board is populated with various components (IC, RAM, solid state memory, processing units, transistors, capacitors, diodes, varistors) that are generally included in a PCB for mobile devices. As the goal of Pilot 2.1 is to compare a traditional PCB manufacturing with LDS in a way that only the processing step changes and the components stay the same, the Ecoinvent process was modified by removing all components.

The PCB is currently manufactured in Portugal with components coming from China. In the future, it is assumed that the whole production with printed electronics can be in Europe which will significantly reduce transportation related emissions.

The size of PCB in Pilot 2.1 application is 15 x 11 mm. The PCB also has a casing made from ABS that weights 0,6 grams.

4.1.4. Life Cycle Impact Assessment and scenario analysis

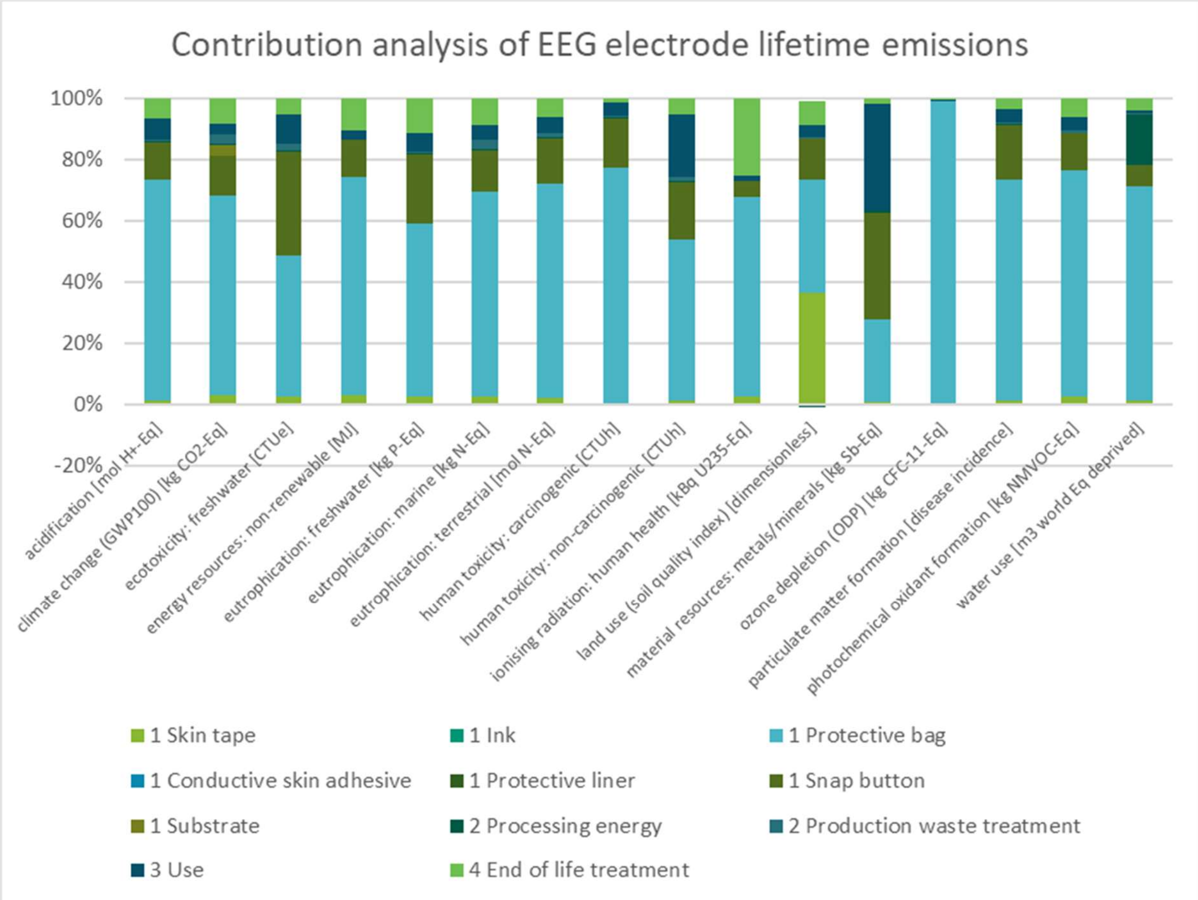


Figure 13 presents a contribution analysis of the lifetime impacts associated with the EEG electrode, broken down by both materials and manufacturing processes. It highlights which components of the electrode's production are most significant in terms of environmental burden, allowing for a clearer understanding of the relative impact of raw materials versus processing steps.

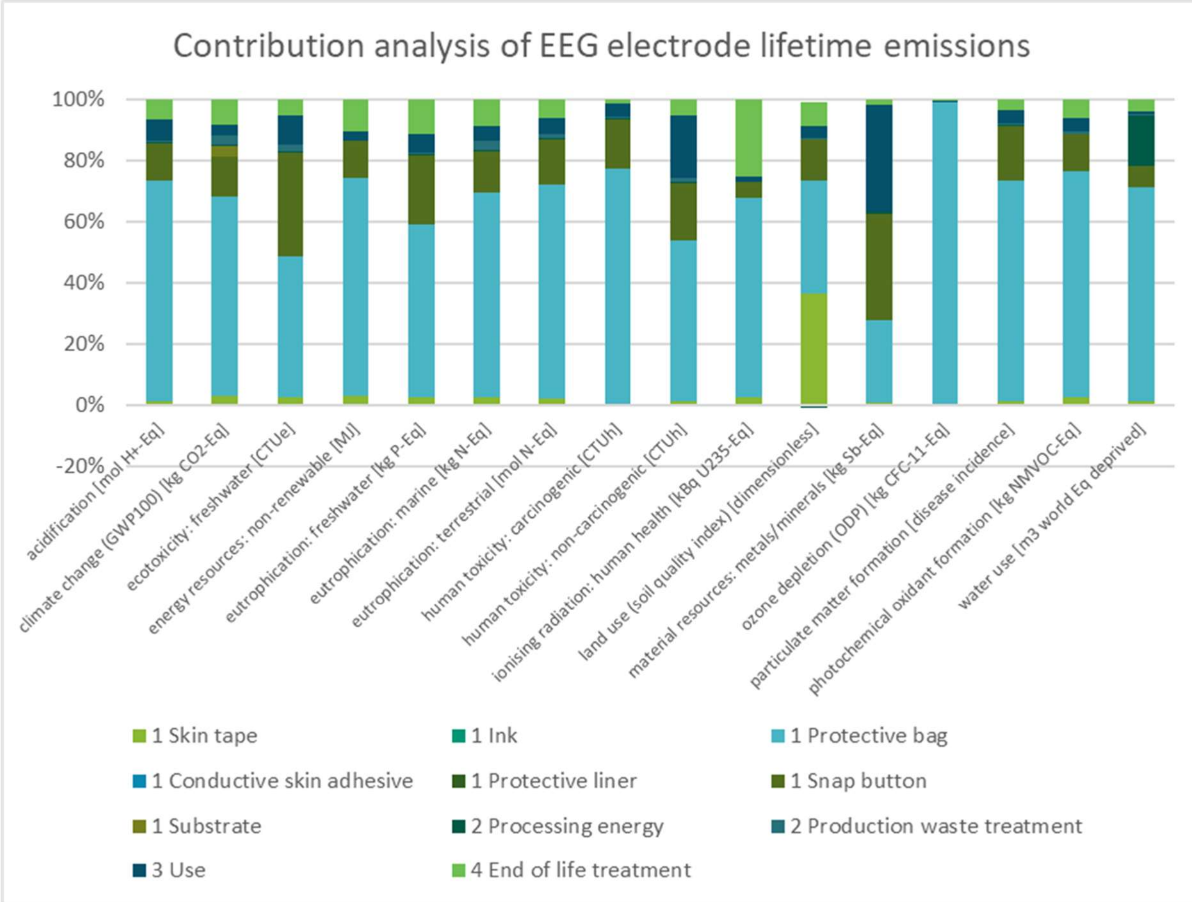


Figure 13: Contribution analysis of EEG electrode lifetime emissions.

Materials cause a big portion of the electrode's lifetime environmental impacts. Protective bag is the biggest contributor to almost all impact categories except material use (mineral and metals) which shows significant impacts also snap button and use. The protective bag is made from PET and has an aluminium layer made from primary material. The aluminium is responsible for most of the bags impacts. Skin tape shows markable impact in land use. This is because the tape is mostly paper and paper manufacturing impacts land use via forestry. Copper ink has an impact on resource use (mineral and metals). Other visible impacts arise from the snap button and end-of-life.

Figure 14 shows the contribution analysis results for lifetime impacts of the EEG sensor where the sensor manufacturing is divided into process steps.

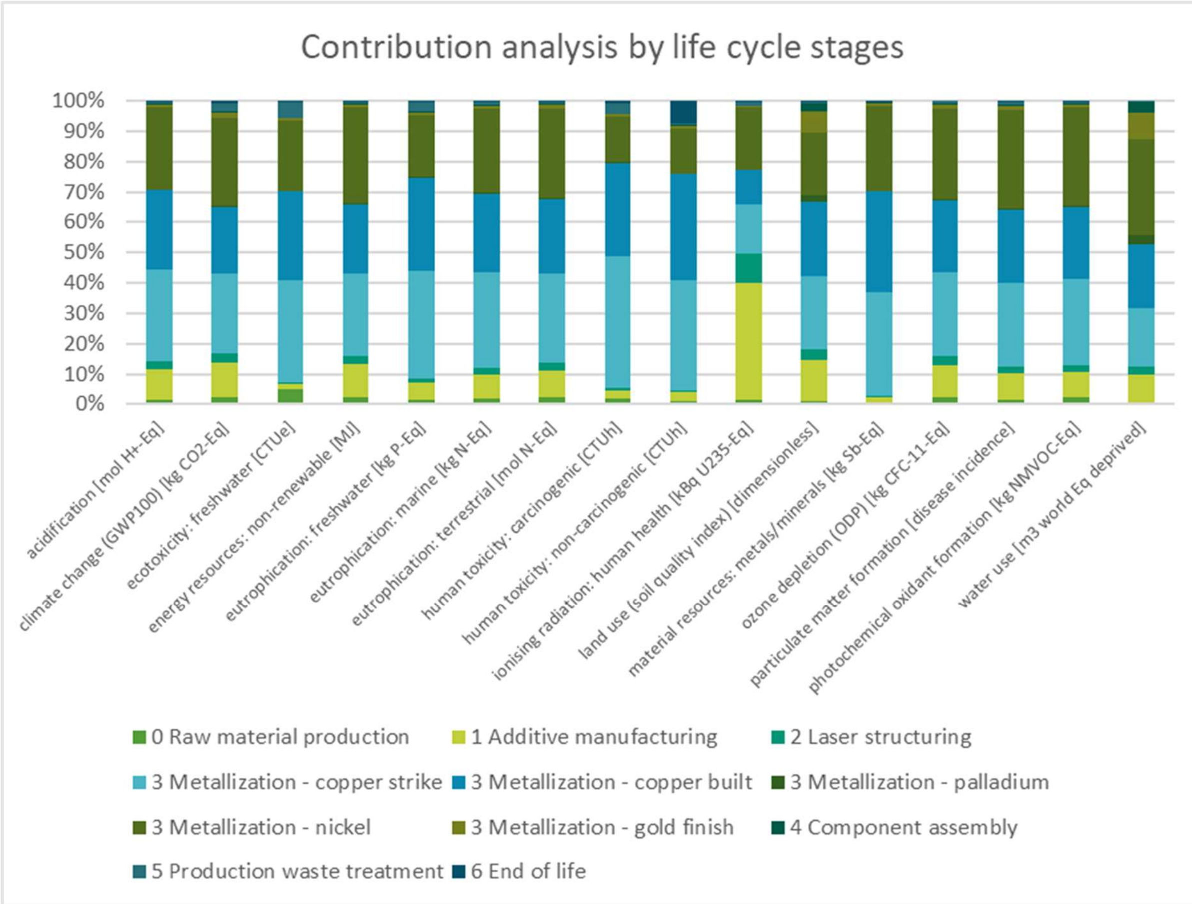


Figure 14: Contribution analysis of LDS sensor lifetime emissions.

The different metallization steps are responsible for approximately 80% of the lifetime environmental impacts of the sensor depending on impact category. Most prominent are the copper and nickel stages. At this point in development, the metallization is done in a laboratory environment with small batch sizes which will have an impact on the results. With enhanced manufacturing routes, the impact of metallization would most likely go down. If the metallization baths are not considered, the additive manufacturing stage becomes prominent as it uses large amounts of electricity. Process optimization could lead to lower emissions from this production stage.

The raw material polycarbonate (PC) is also a cause for some impacts. In this case, 50% of the PC is post-consumer recycled, and increasing this proportion could further benefit the environment. However, the LCI data used for PC in this study is based on an ecoinvent process for fossil-based polycarbonate. It has been modified using data from Plastics Europe (Plastics Europe, 2024), which indicates that 50% post-consumer recycled polycarbonate has 38% less climate impact than its fossil-based counterpart. The ecoinvent process was accordingly scaled down by 38%, which also reduced other impact categories by the same percentage. In reality, these reductions don't apply equally to non-climate-related impacts, and using recycled content may result in even lower impacts for the raw material.

To see the whole system of Pilot 2.1 together, Figure 15 presents the lifetime emissions of electrodes and sensor combined.

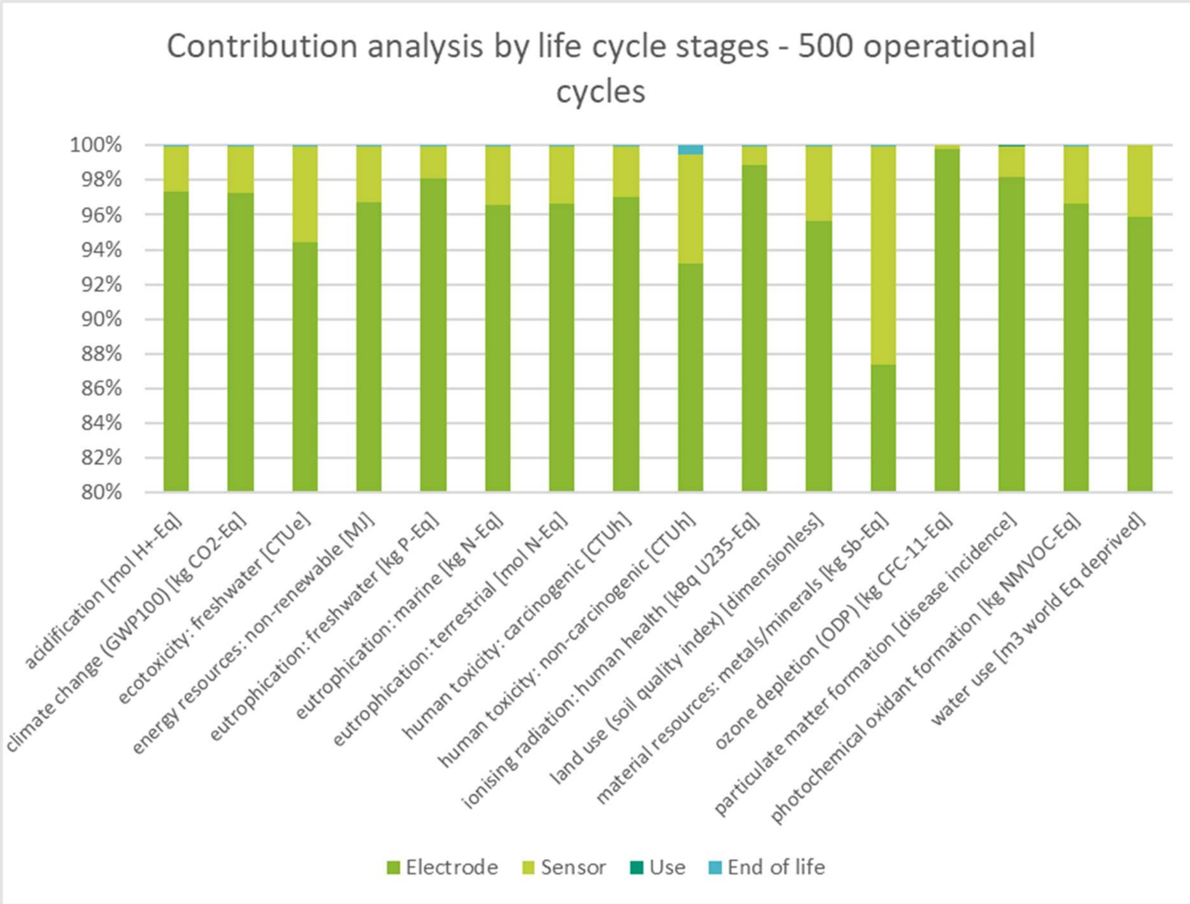


Figure 15: Contribution analysis of EEG electrode and sensor lifetime emissions for 500 measurement cycles.

During use, two single-use electrodes and one sensor are required. This means that for 500 measurements, 1000 electrodes are used. Electrode production accounts for most emissions in all impact categories, while sensor manufacturing contributes only a small percentage. The sensor's long lifespan keeps its per-measurement impact minimal.

Comparison to benchmark

The electrode benchmark is a similar electrode using fossil PET as a substrate. Figure 16 shows the comparison of generation 3 electrode and the benchmark.

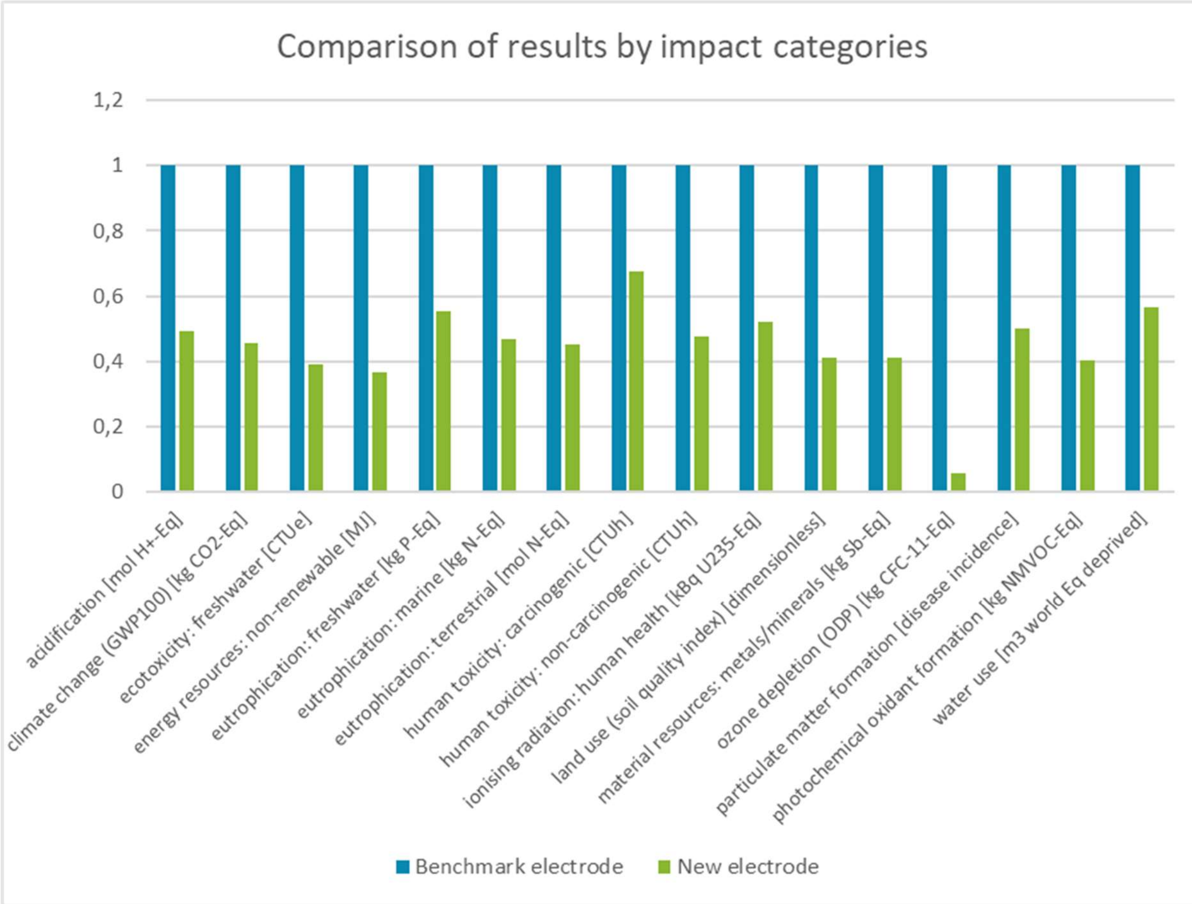


Figure 16: Comparison of baseline electrode and generation 3 electrode.

In comparison with the benchmark electrode, the generation 3 electrode shows significant improvements across all environmental impact categories.

For the sensor, PCB production calculated according to the ecoinvent dataset *printed wiring board production, mounted mainboard, mobile device, double-sided, Pb free* is utilized as a benchmark. The PCB also has a casing made from ABS and together they make the sensor. Figure 17 shows the comparison of between manufacturing one baseline sensor and one LDS sensor. Use and end-of-life are excluded.

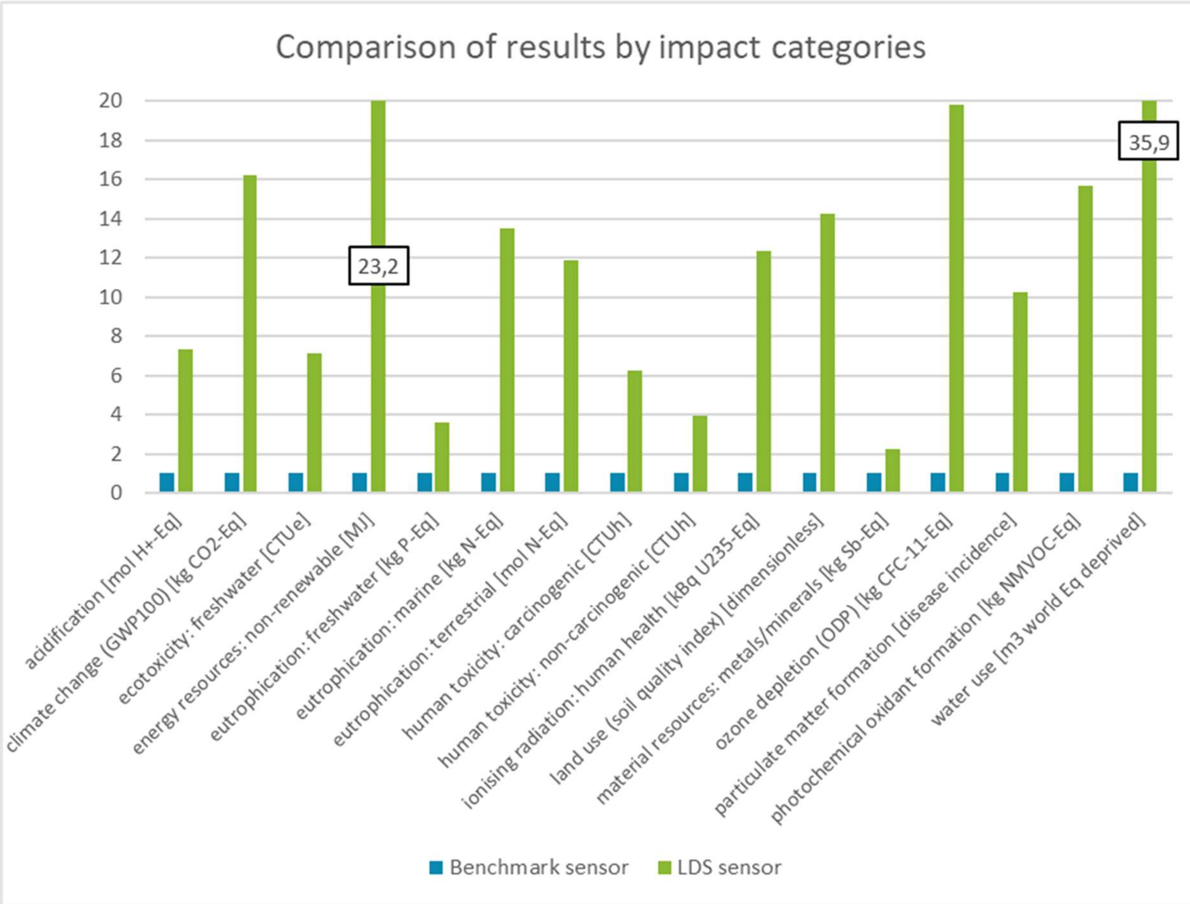


Figure 17: Comparison of baseline sensor and LDS sensor manufacturing. Use and end-of-life are excluded.

According to the results, the final prototype LDS sensor has higher environmental impacts in all studied impact categories. Most of these impacts come from the metallization steps. As the sensor production is still in laboratory scale, the metallization baths are used only once to make a batch of 10 sensors. In industrial scale manufacturing, these baths could potentially be reused hundreds of times by adding small amounts of chemicals to them intermittently to keep them usable. Also, the polymeric part could be manufactured using injection moulding (IM) instead of additive manufacturing (AM). The impact of these changes was studied next.

Industrial scale manufacturing

As the metallization step, and the chemical baths used in it are the cause of most of the impacts from sensor manufacturing, a sensitivity analysis was performed to see the impacts of reusing these baths as would be the case in an industrial scale manufacturing plant. For the sensitivity analysis, three additional scenarios were created:

1. Baseline – polymeric part is manufactured using AM and chemical baths are not reused
2. Reuse – polymeric part is manufactured using AM and chemical baths are reused 100 times
3. Injection moulding + reuse – polymeric part is manufactured using IM and chemical baths are reused 100 times

Figure 18 shows the impacts of reusing chemical baths and switching from additive manufacturing to injection moulding to the overall environmental impacts of LDS sensor manufacturing using the polyethylene furanoate (PEF) single score.

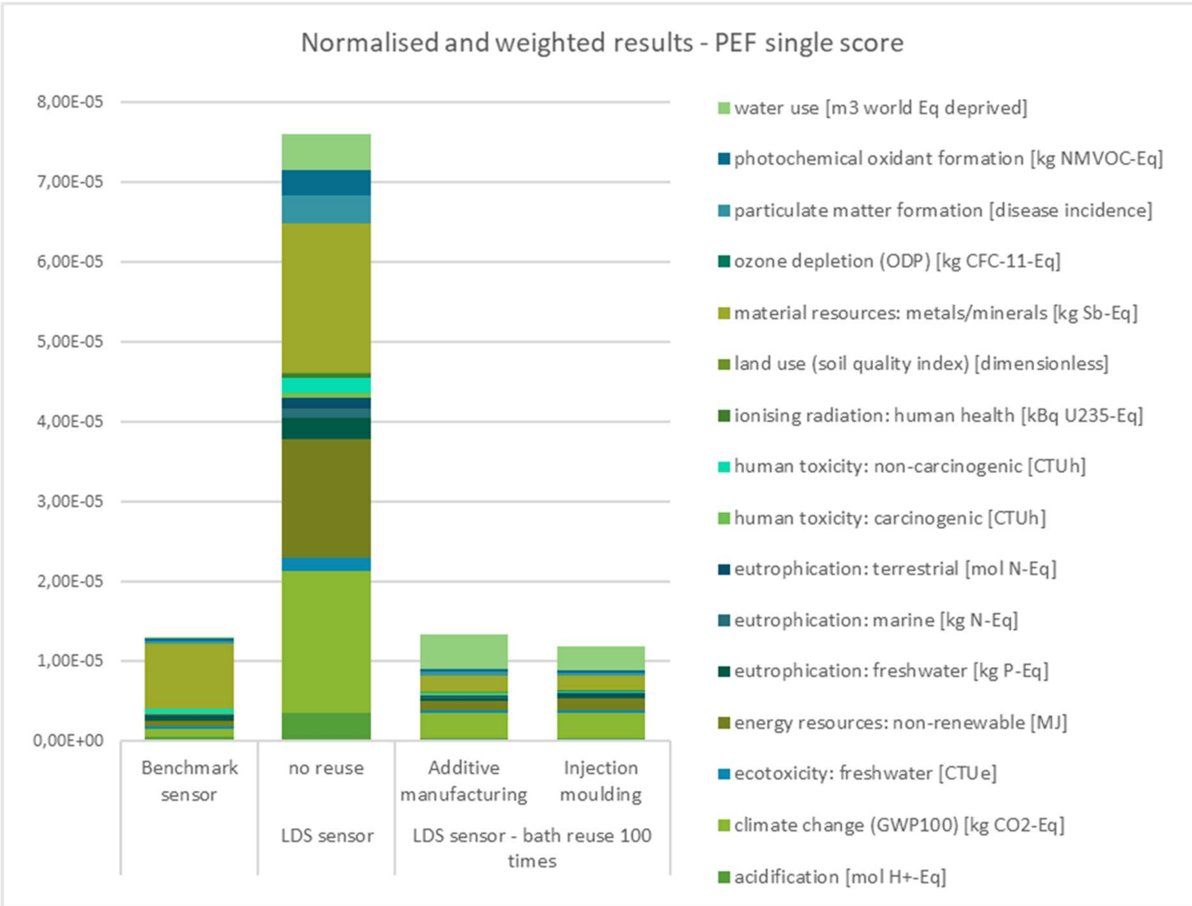


Figure 18: Sensitivity analysis of chemical bath reuse and polymeric part manufacturing presented as PEF single score.

Figure 18 illustrates the effect of chemical bath reuse on the environmental impacts of LDS sensor manufacturing, as measured by the PEF single score. When chemical baths are reused, the overall environmental impact decreases significantly. Reusing baths 100 times (scenario 2) results in a noticeable reduction, while simultaneously changing from AM to IM (scenario 3) further lowers the environmental footprint, demonstrating a clear benefit to sustainability. Compared to the benchmark sensor, material resources (minerals and metals) impact could potentially be 80% lower in scenarios 2 and 3. This trend highlights the importance of process development, as repeated use of chemical baths minimises waste and reduces the need for fresh chemicals, thereby lessening the environmental burden associated with sensor production. In industrial scale manufacturing using IM technology and reusing chemical baths, the LDS sensor could have lower overall environmental impacts than the benchmark.

While the reuse of chemical baths significantly reduces environmental impacts, the remaining impacts are largely attributed to the raw material polycarbonate (PC). At present, the used polycarbonate contains 50% recycled content, but increasing this proportion could further decrease the environmental footprint. Using more representative LCI data could also result in lower impacts as discussed before. Additionally, optimising energy consumption during the polymeric part manufacturing step would yield even greater reductions in overall impacts, highlighting further opportunities for sustainability improvements in LDS sensor production.

4.1.5. Conclusions

In summary, the Pilot 2.1 study demonstrates notable progress in reducing the environmental impacts associated with EEG electrode manufacturing. When compared to established benchmarks, the generation 3 electrode shows significant reductions in several key impact categories, including freshwater eutrophication, human toxicity, acidification, particulate matter, and material use. The impacts of LDS sensor manufacturing show there is potential as well. The metallization stages, particularly copper and nickel, currently account for most lifetime environmental impacts of sensor manufacturing. Adopting chemical bath reuse in manufacturing could lead to substantial improvements in the environmental profile of LDS sensors, making the production process more resource-efficient and environmentally friendly. Furthermore, changing from additive manufacturing to injection moulding could lead to even lower impacts. These findings highlight the potential of the developed technologies to enhance sustainability in electronic sensor systems and highlight the importance of ongoing optimization in production processes.

4.2. Pilot 2.2

4.2.1. Introduction

Pilot 2.2 is part of the Sustainable manufacturing for electronics use case and aims to develop wearable health manufacturing devices. It is led by SCR with contributions from MOV, UPM, TER, EDI, TAU and VTT. The target of this pilot is to demonstrate the developed technologies for more sustainable wearable systems for health monitoring.

Life Cycle Assessment is used to identify the key environmental impacts of the current prototypes. LCA focuses on single use or multi use medical electrodes for ECG (electrocardiography) and bio-impedance monitoring by using more sustainable materials.

4.2.2. Scope of the Study

Scope of the study is cradle-to-grave with especial focus on cradle to gate for the electrodes as those are the steps that the pilot partners have control over. Use stage is based on estimations by pilot partners and end of life is also an estimate based on literature and assumed treatment routes.

The electrodes are used in measuring together with a sensor, but that sensor is not included in this study, only the battery that's used by the sensor.

The baseline LCA model represents the configuration corresponding to the prototype of generation 3, although different configurations are still possible. As with the pilots in case study 1, no specific cut-off rules were applied in this LCA; data availability served as the primary inclusion criterion. Further details regarding the included processes are outlined in the subsequent section.

As the goal of Sustronics is to study the lifetime impacts of these novel pilot applications, it is important to set the system boundary of the LCA to match that ambition. Therefore, the complete life cycle assessment is done cradle to grave, meaning all impact from raw material extraction up till end-of-life processes are considered. Setting the system boundary as such, brings up an important notice considering biogenic carbon. Many of the materials under study are either cellulose based or contain other biobased materials which in turn contain biogenic carbon. According to (Pawelzik, et al., 2013) biogenic carbon can be considered in two ways:

1) Biogenic carbon is accounted for as carbon storage considering CO_2 is captured from atmosphere during photosynthesis and retained within the material (cradle to gate LCA)
2) Biogenic carbon is considered CO_2 neutral and excluded from the analysis at the end of life (cradle to grave LCA)

The 1st generation assessment was only cradle to gate but as the final 3rd generation study was cradle to grave, approach (2) was followed through-out all three generations. It is important to notice that all carbon storages are reversed when the product is either burned or biologically degraded at end of life. For the assessment results to be comparable, it is imperative that all materials consider biogenic carbon in the same way. At the moment, that is not done due to different data sources, which means climate change impacts between different materials are not completely comparable.

The selected EoL allocation approach is 0/100, which incorporates credits for the avoided production of recycled components. These credits are presented separately to maintain clarity.

EF3.1 methodology was used for calculating midpoint impact indicators. The report focuses on a selected list of relevant indicators but presents all 16 environmental impact categories.

4.2.3. Life Cycle Inventory

Baseline model

The electrodes are divided into materials: substrate, printing paste, hydrogel, skin adhesive, liner, snap button and moisture barrier foil. There were three parallel electrode developments on-going, two for MOV and one for EDI. The designs were slightly different but utilized partly the same materials. For MOV, one electrode was designed to be single-use, and the other reusable. The reusable electrode also includes a washable belt where the electrode is integrated. For EDI the electrode was single use. Due to time constraints, only the MOV electrodes are included in this deliverable.

Similarly to Pilot 2.1, the electrode is based on a substrate onto which conductive traces are printed using conductive ink. Hydrogel and skin adhesives are used for additional properties. There is also a paper based protective liner, a protective bag and stainless-steel snap buttons included in the configurations. More details on performance of the materials and processes are reported in WP1 deliverables D1.4 (Sustainable materials and their characteristics, M18), D1.5 (Sustainable processes and their characteristics, D1.5) and D1.6 (Material and process validation and testing results, M24).

Primary data on ink production was not available, so product technical data sheets (TDS) and safety data sheets (SDS) were used instead to estimate their composition. Ink production energy was modelled similarly as in Pilot 2.1 by using ecoinvent data.

For generation three, there were four alternative substrates tested in the electrodes: white coated paper, brown paper, 40% post-consumer recycled (PCR) PET and fossil PET. Environmental impact data for paper substrates and PCR PET manufacturing was received from pilot partners. Fossil PET was modelled using ecoinvent data.

Ink options for MOV electrodes were one copper and two carbon alternatives. Table 6 lists the composition of these inks and modelling assumptions.

Table 6: Composition of inks used for LCA modelling in Pilot 2.2 including assumptions.

Ink	Chemical	Share	Modelled as
Copper paste	copper	65%	copper, anode
	binder	30%	chemical, organic
	silver	5%	silver
Carbon paste 1	DE acetate	60%	ethylene glycol monoethyl ether
	carbon black	40%	carbon black

Carbon paste 2	2-(2-butoxyethoxy) ethanol	22.5%	reaction of 1-butanol + ethylene oxide
	graphite	25%	graphite
	2-(2-butoxyethoxy) ethyl acetate	40%	2-(2-butoxyethoxy) ethanol
	phenoxy resin	15%	epoxy resin

Use phase is modelled based on data provided by SCR and MOV. One measurement cycle for MOV electrodes is set to 10 h. A Li-ion battery is used as the power source for the measurements. One battery can last up to 168 h, and the studied timeframe for lifetime emissions is one year. Measuring is done daily and a new electrode is used each time in the single use case. For reusable MOV electrode, the belt is washed once a week, after every seven uses. The reusable electrode can last a years' worth of measuring.

The electrodes are assumed to be properly sorted into WEEE and medical waste fractions respectively while the batteries are sent to WEEE treatment. Efficient separation of electrode and battery is assumed. Electrode is assumed to go to medical waste treatment using steam sterilization, followed by incineration, while the WEEE fractions are assumed to go to shredding and ultimately smelting-based metal recovery and plastic recycling.

The model has been built using Sulca LCA tool as software. The background data has been pulled from the Ecoinvent 3.11 database and Sphera LCA for Experts database.

Benchmark

There was no benchmark for the electrode, so the comparison point was generation 3 electrode using fossil-based PET as a substrate, silver ink and an aluminium lined protective bag as that reflects the state-of-the-art materials.

4.2.4. Life Cycle Impact Assessment and scenario analysis

During Gen 3 development, four types of conductive inks were evaluated for their suitability in electrode fabrication, each offering distinct advantages depending on their material composition. Figure 19 below illustrates a comparison between the standard benchmark electrode (PET and silver) and three different ink options applied to a paper substrate: one utilising copper and two using carbon-based formulations. These inks were selected to investigate how varying the conductive material influences the performance, sustainability, and environmental impact of the electrodes. Silver ink is the standard nowadays, known for its excellent electrical conductivity, while the copper and carbon inks may offer benefits such as lower cost, improved flexibility, or reduced environmental footprint.

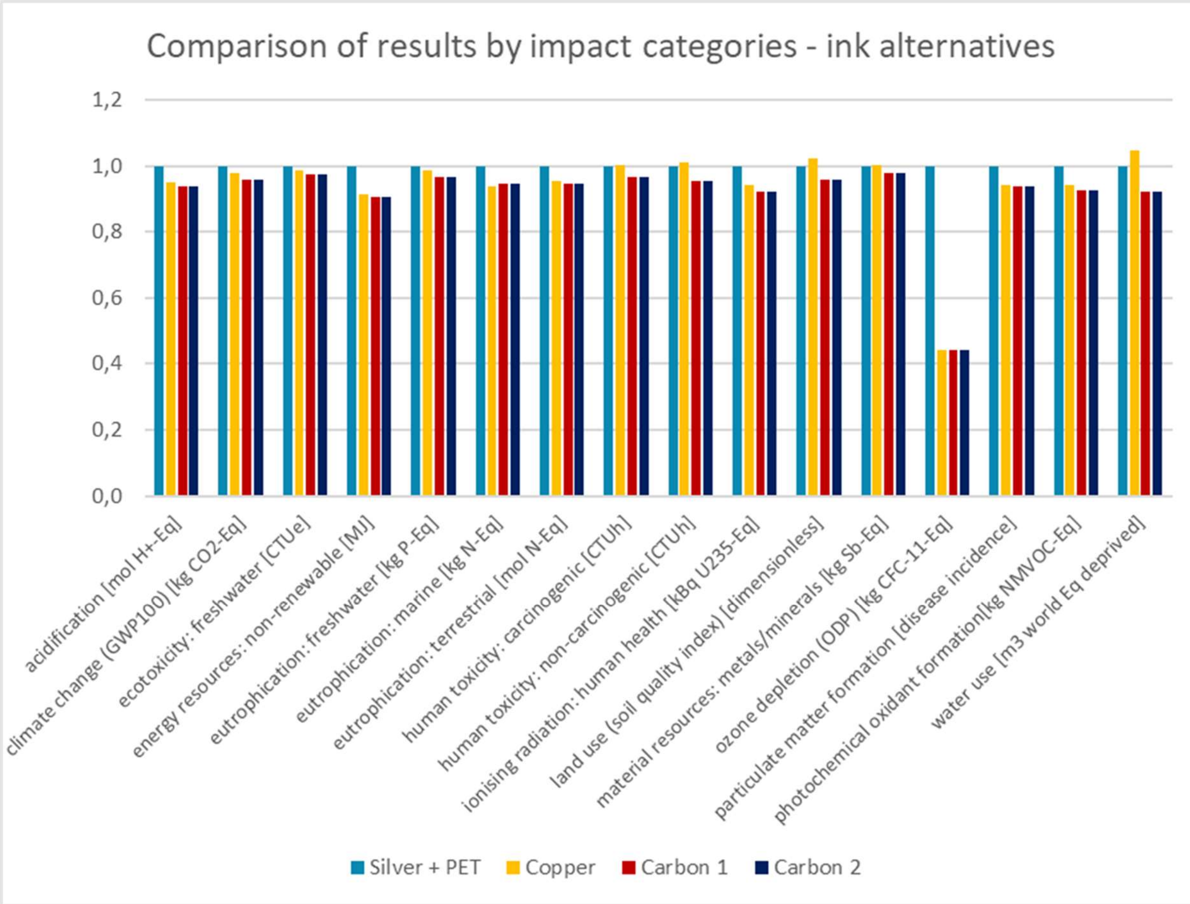


Figure 19: Comparison of different ink alternatives on paper substrate.

Figure 19 shows that out of the new alternatives, silver ink has the largest environmental impacts across most categories, while carbon ink offers minor improvements in water use, land use, and human toxicity. However, these differences are only a few percent and do not justify definitive claims about either ink's benefits. Compared to benchmark silver ink, all alternatives show improvements.

In the assessment, four substrate alternatives were also evaluated: fossil-based PET, 50% post-consumer recycled (PCR) PET, and two types of paper. Fossil PET represents the conventional plastic substrate derived from non-renewable sources, while PCR PET is manufactured from recycled PET plastic, offering potential reductions in environmental impact due to circularity and resource conservation. The two paper substrates provide a renewable, biodegradable option, with each type differing in manufacturing process or fibre composition.

Figure 20 shows the comparison using copper ink.

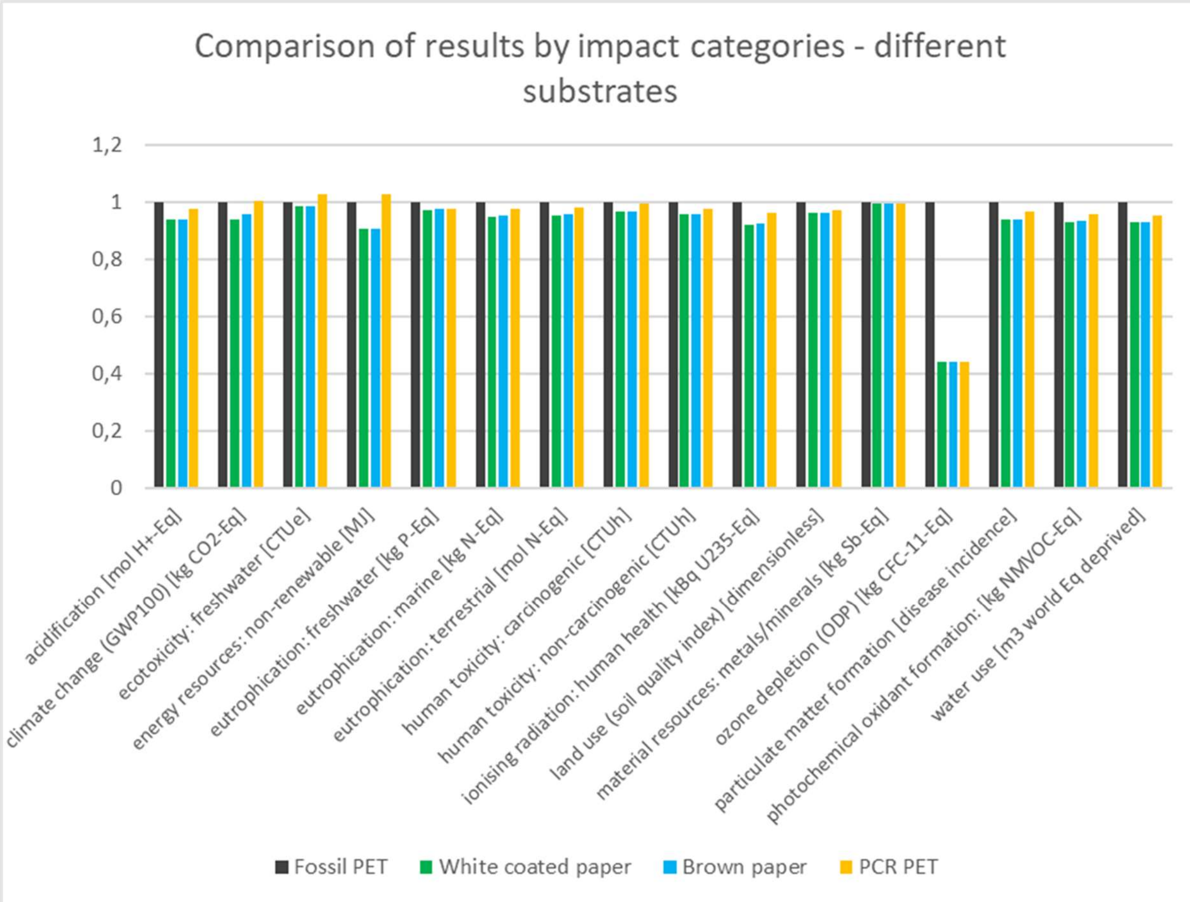


Figure 20: Comparison of different substrate alternatives on electrodes made with copper ink.

When comparing the alternative substrates, the fossil PET generally exhibited the highest environmental impacts, particularly in categories such as climate change, energy resource use, and ozone depletion. The alternative substrates performed favourably in several impact categories, but the difference to fossil PET was minimal in all categories but ozone depletion, where the difference is approximately 55%. As with the inks, definitive claims cannot be made but the results suggest that shifting from fossil PET to PCR PET or paper substrates can deliver environmental benefits in some areas. It should be noted that the paper substrates only have climate change impact associated with them due to restriction in available data. Therefore, it is possible that impacts arising from the two paper alternatives are higher than now presented. Especially in land use category, forestry would likely have a noticeable impact.

The electrode has many other materials besides ink and substrate. The whole electrode is presented below in Figure 21 together with use and end-of-life stages.

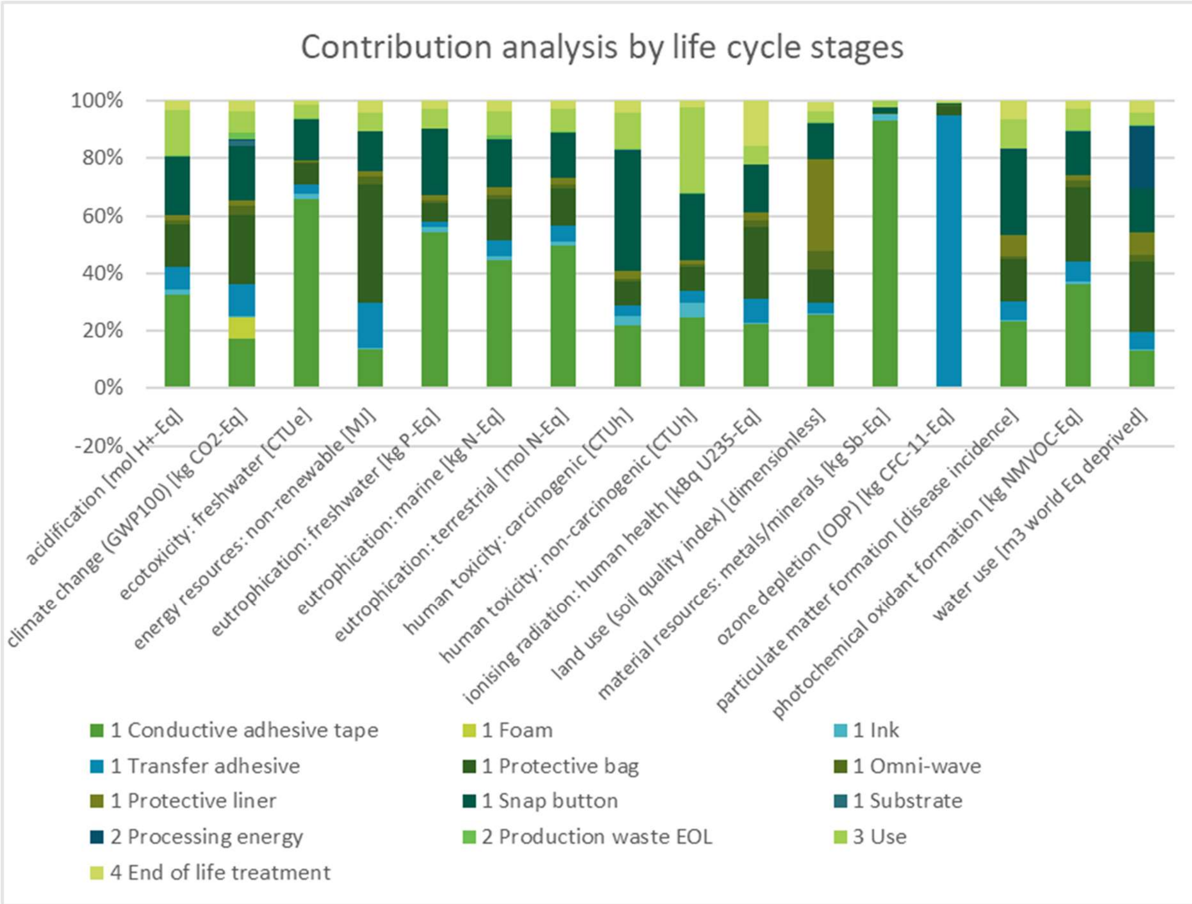


Figure 21: Contribution analysis of single use electrode lifetime emissions.

The results demonstrate that while manufacturing remains the primary contributor to environmental impact, use and end-of-life have a measurable impact as well. Conductive adhesive tape is responsible for substantial impacts in almost all impact categories, especially ecotoxicityicity, eutrophication and material resource use (minerals and metals). Silver in the adhesive is responsible for most of these impacts. The protective bag is responsible for the biggest share of impacts in energy resources (non-renewable) and shows high impacts also in climate change, ionising radiation, photochemical oxidant formation and water use. The substrate material, white coated paper, does not show considerable impacts in climate change, which is the only category it affects due to the used data, while the protective liner shows considerable impacts only in land use. Transfer adhesive on the other hand dominates ozone depletion but has minimal impacts elsewhere. Impacts from other materials vary across impact categories. If more comprehensive data was available for the paper substrate, it would most likely show a moderate impact at least in land use due to forestry.

Single use vs. multi-use

One of the targets of Pilot 2.2 was to demonstrate single use and multi-use medical electrodes. This sensitivity analysis compares the two designs during one year of measurements. The specifics of each electrode use are:

- single use: 365 electrodes, measurement length 10 h/day, powered by a Li-ion battery that lasts 168 h.
- multi-use: 1 electrode, 1 belt + buckle, measurement length 10 h/day, powered by a Li-ion battery that lasts 168 h. Electrode, belt and buckle are washed in washing machine using a 30 °C cycle every week.

Figure 22 below shows lifetime emissions for the reusable electrode.

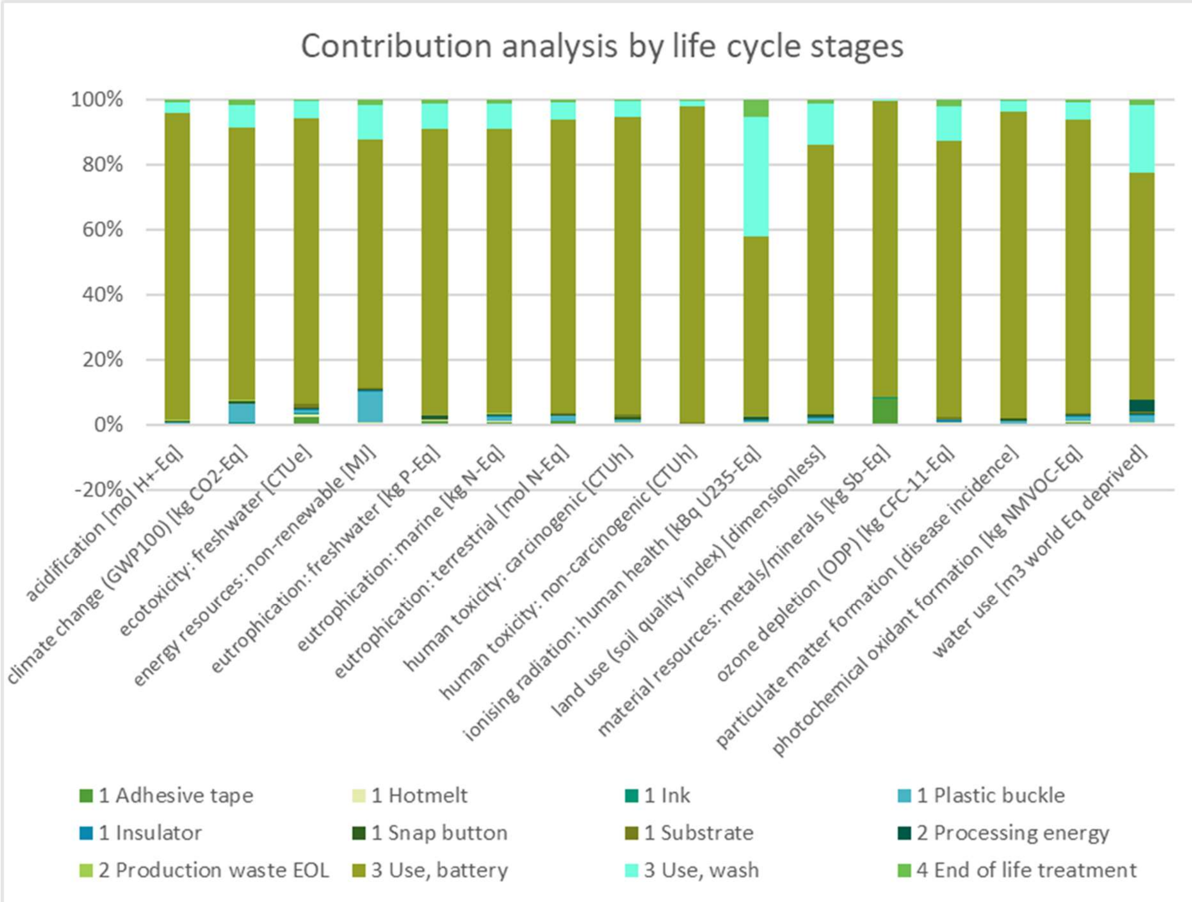


Figure 22: Contribution analysis of reusable electrode lifetime emissions.

From Figure 22, washing and changing the battery contribute the most to the lifetime emissions of reusable electrode. This is to be expected as for example manufacturing of Li-ion batteries is known to have big impacts to the environment and washing cycles require energy as well as detergents.

Comparing single use to reusable option is done below in Figure 23.

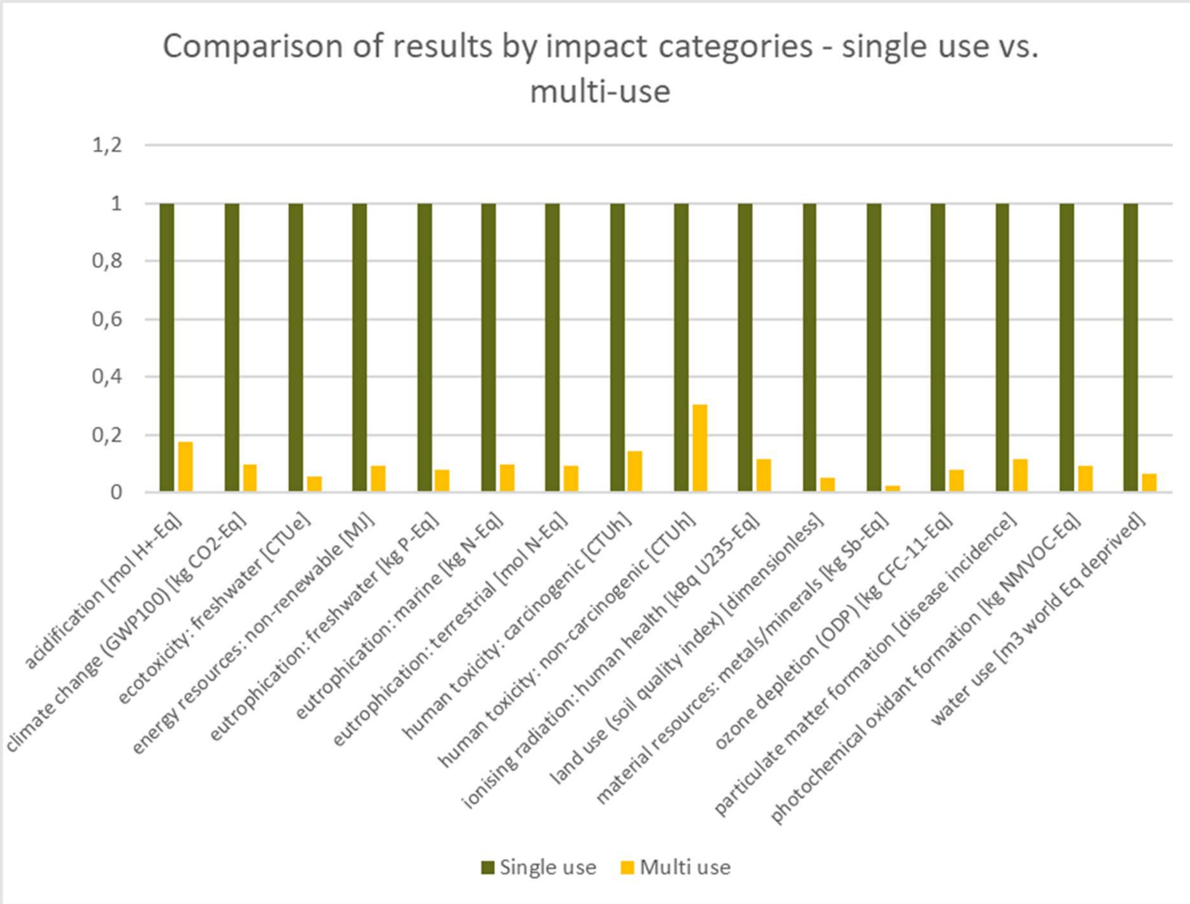


Figure 23: Comparison of single use electrode and reusable electrode lifetime emissions for 1 year.

Figure 23, comparing single use and reusable electrode lifetime emissions over one year, illustrates a marked difference between the two options. It is evident that the reusable electrode, despite the emissions associated with washing and battery replacement, results in significantly lower overall emissions compared to the single use alternative. The single use electrodes accumulate emissions rapidly due to the manufacturing requirements for each individual unit, whereas the reusable option spreads its environmental impact across multiple uses, making it a more sustainable choice in the long term.

The lifetime of multi-use electrode was varied in a sensitivity analysis studying only the climate change impact to see at which point the reusable electrodes becomes better. This is depicted below in Figure 24.

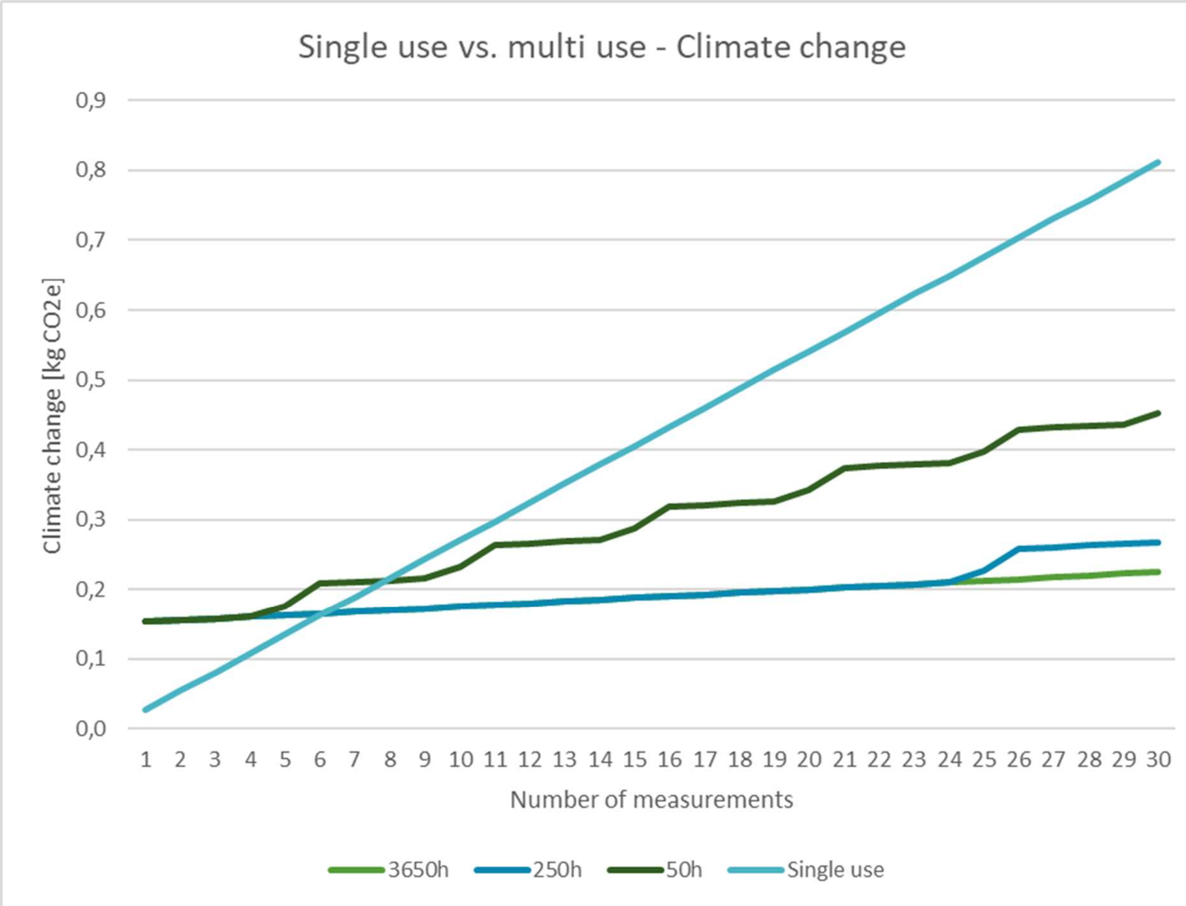


Figure 24: Single use and multi-use break-even curve for climate change (EF3.1).

From Figure 24, the reusable electrode with washable belt has higher climate change impact only for the first six measurement cycles if the reusable electrode has a lifetime of 3650 h. When electrode lifetime is decreased to 50 h, the break-even point is reached after eight measurement cycles. After that, the single use electrode has higher impacts.

4.2.5. Conclusions

The assessment of Pilot 2.2 clearly highlights that environmental impacts from manufacturing have big impact on the lifetime emissions of single use medical electrodes. The analysis found that the conductive adhesive tape is responsible for a substantial amount of impacts in almost all impact categories, especially ecotoxicityicity, eutrophication and material resource use (minerals and metals). Silver in the adhesive is responsible for most of these impacts. The protective bag is responsible for the biggest share of impacts in energy resources (non-renewable) while snap button shows considerable impacts in land use. Transfer adhesive on the other hand dominates ozone depletion but has minimal impacts elsewhere. Impacts from other materials vary across impact categories. The sensitivity analysis demonstrated that reusable electrodes with washable belts offer considerable improvements over single use options in all impact categories, already after six measurement cycles.

4.3. Pilot 2.3

4.3.1. Introduction

Pilot 2.3 is part of the *Sustainable manufacturing for electronics* use case and aims to develop an innovative automotive dashboard offering a more comfortable and pleasant user experience for drivers, while answering the need for a green and circular approach. It is led by FAU with contributions from CEA, SYM, ARNP, RISE, MIR and VTT. The dashboard is based on the combination of In-Mold Electronics, as an alternative to conventional PCBs, and bio-based substrates.
Life Cycle Assessment is used to identify the key environmental impacts of the current prototype.

4.3.2. Scope of the Study

This LCA is cradle-to-grave, covering all relevant life cycle phases from raw materials acquisition to End-of-Life (EoL). The main focus of the analysis is on the production phase, since it's the phase that FAU has the most control over and where the dashboards design has the biggest effect. However, the scope was set at cradle-to-grave to also include potential end-of-life routes.

The baseline LCA model represents the configuration corresponding to the prototype of generation 3, although different configurations are still possible. As with the pilots in case study 1, no specific cut-off rules were applied in this LCA; data availability served as the primary inclusion criterion. Further details regarding the included processes are outlined in the subsequent section.

The selected EoL allocation approach is 0/100, which incorporates credits for the avoided production of recycled components. These credits are presented separately to maintain clarity.

EF3.1 methodology was used for calculating midpoint impact indicators. The report focuses on selected relevant indicators.

4.3.3. Life Cycle Inventory

Baseline model

The automotive dashboard is composed of three parts: decorative film, electronic/technical film and housing. Primary data about the production of each part was collected from pilot partners. This data was then supplemented with Ecoinvent data to create the lifecycle model. The primary data is confidential and won't be shared in this deliverable.

The dashboard has two specific areas:

- Left side is a dynamic lighting area composed of various SMDs (Single Mounted Device), a microcontroller (LED (Light Emitting Diode) driver) and 8 RGB LEDs.
- Right side is an active command with one capacitive back lighted slider on the top and 3 capacitive backlighted buttons below. 2 RGB LEDs per button and 4 RGB LEDs are on this part of the technical film together with a microcontroller, resistors and capacitors.

Two potential materials for the housing and films were considered, bio-based polycarbonate (PC) and polyethylene furanoate (PEF).

LCI for bio-based PC was taken from a public report by Sabic (Sabic, 2021) which was used to scale the Ecoinvent fossil-PC production process based on Sabics reported carbon footprint deduction, as for PEF, an Avantium study by nova Institute was used (Nova Institute, 2022).

In generation 3, the focus was on end-of-life options and recyclability. No changes in product design were made.

Benchmark

Benchmark for the dashboard is the configuration of generation 1, which is a similar dashboard made using fossil PC.

4.3.4. Life Cycle Impact Assessment and scenario analysis

The production of dashboard has been divided into four steps:

1) Decorative film production
2) Electronic film production
3) PC/PEF pellet production for housing
4) PC/PEF injection for housing

Figure 25 shows the contribution analysis results for a dashboard made using PEF and Figure 26 similarly for a dashboard using bio-PC.

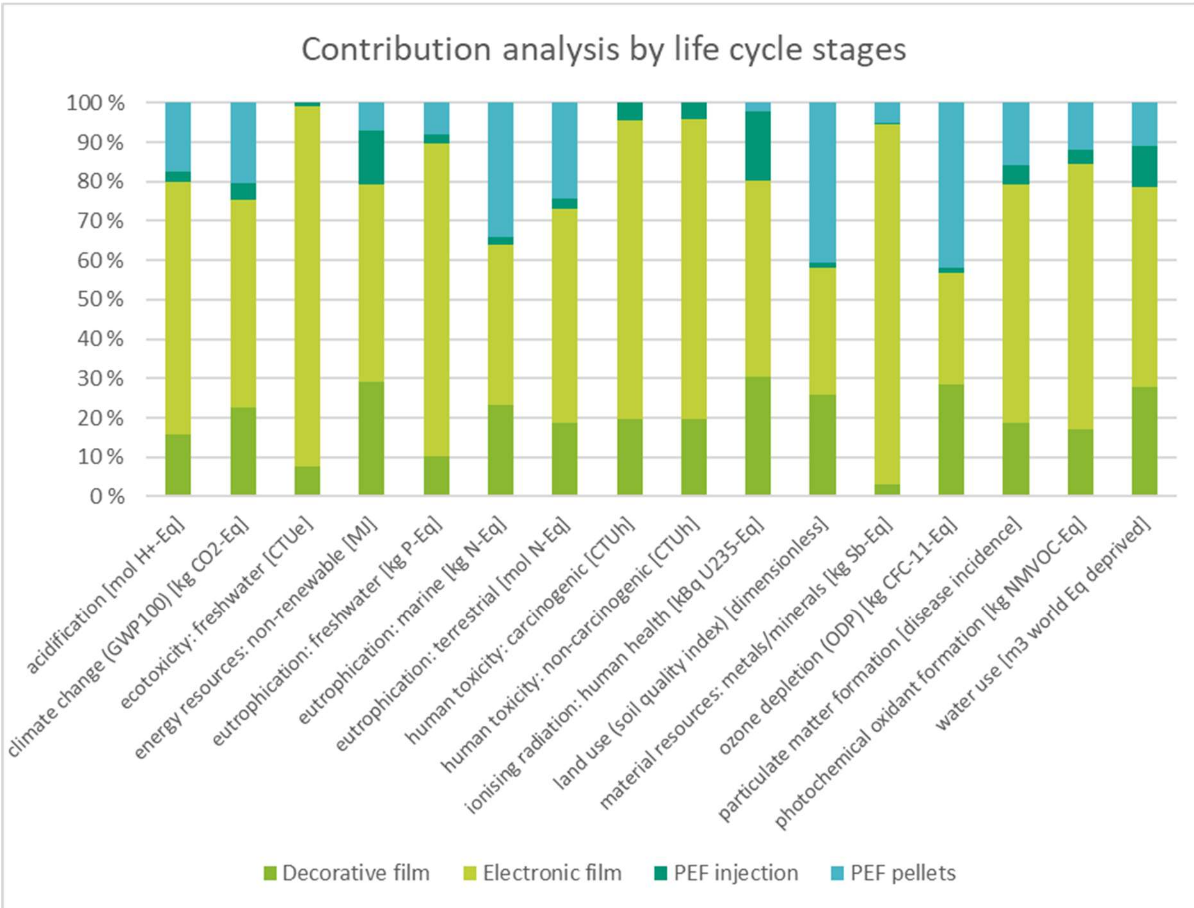


Figure 25: Contribution analysis of automobile dashboard manufacturing emissions using PEF.

The impacts are similar for both materials, with the electronic film causing the bulk of impacts in most categories followed by the decorative film and the housing. The electronic film has many components like LEDs and capacitors which have high environmental impacts. It seems that PEF has a significant impact on ozone depletion and land use as well as marine eutrophication while bio-PC shows lesser impacts in those categories. Although, it is possible that the bio-PC impacts are not representative due to the underlaying LCI data for fossil production, so comparison is not advised.

The PEF material is missing impacts to ecotoxicityicity and both human toxicity categories as those were not available in the reference data that was used to model the material. Therefore, for those three categories it is not possible to explicitly say what the role of PEF would be. Similarly, for bio-PC, the available data on environmental impacts was sparse, only carbon footprint was available. Rest of the impacts were scaled from fossil PC production based on that and may not be completely representative of the material. In the Sabic brochure for bio-PC, it is said that environmental trade-offs in eutrophication and water consumptions are to be expected when using bio-based feedstock. Therefore, it may be that bio-PC has higher impacts in those categories than the current study would suggest, potentially as high as PEF as they both derive from bio-based materials.

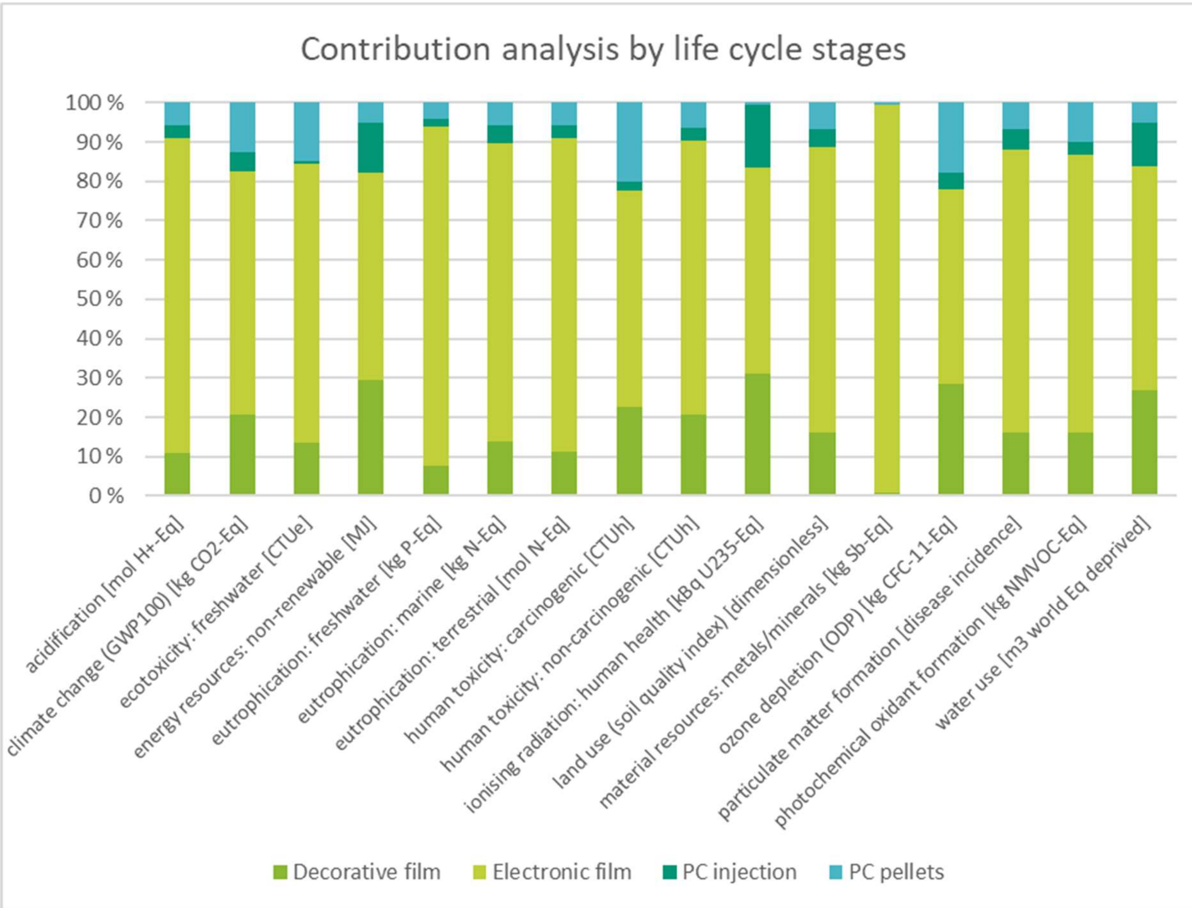


Figure 26: Contribution analysis of automobile dashboard manufacturing emissions using bio-PC.

Two alternative end-of-life routes were studied for the bio-PC and PEF dashboards.

1. Incineration. Includes incineration as municipal solid waste, treatment of incineration residues, separation of aluminium and copper from the bottom ash and preparing them for recycling. Credits are gained from energy substitution.
2. WEEE recycling. Includes shredding and sorting of materials, recycling of plastics and metals. Credits are gained from material substitution.

Figure 27 and Figure 28 show the comparison of climate change impacts between generation 1 and generation 2 and including the possible end-of-life options and credits from material and energy substitution.

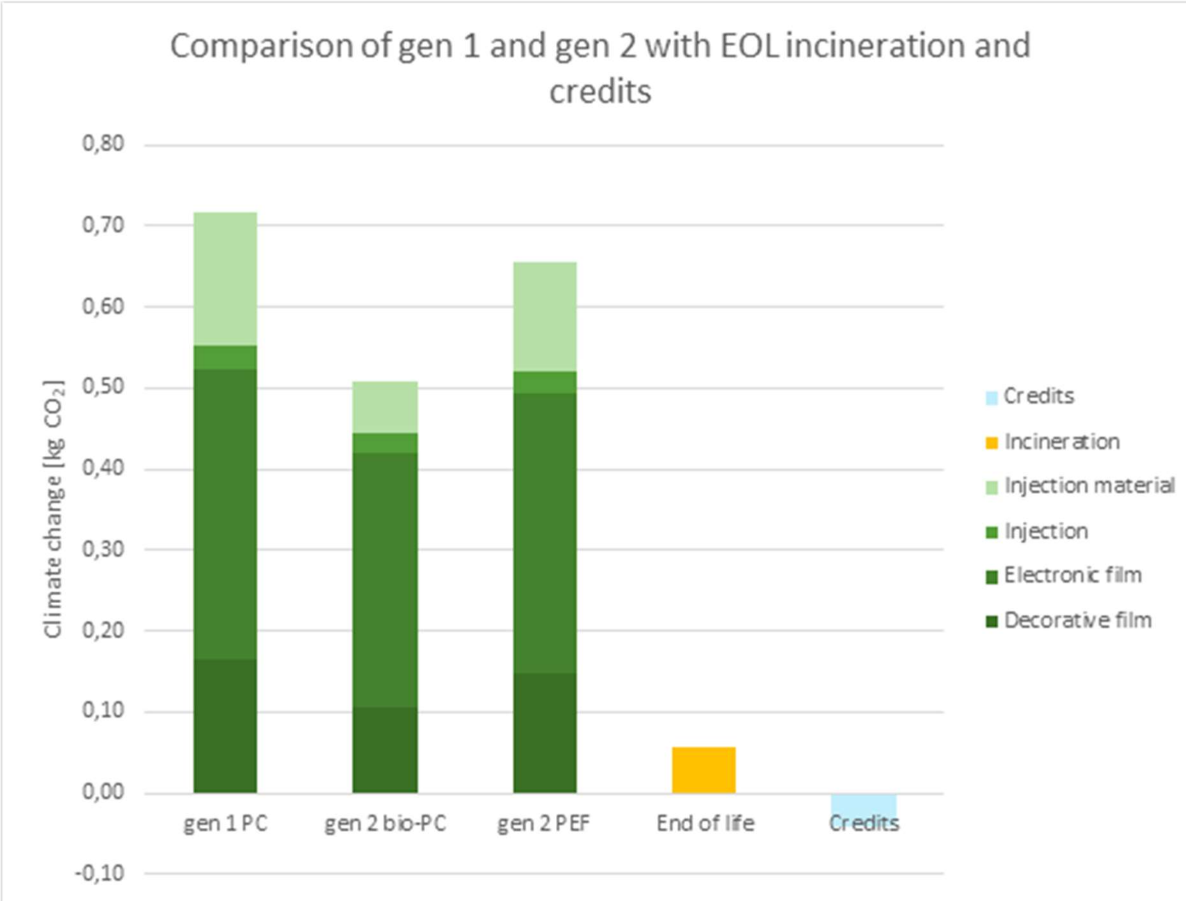


Figure 27: Comparison between climate impacts of generation 1 and 2 dashboards with end-of-life incineration and potential credits from substitution included.

Incinerating the dashboard at end-of-life results in low impacts to climate change. The potential credits from material and energy substitution almost offset those impacts. In this case, incineration includes the treatment of residues at landfill and the separation and refining of recovered copper. Credits arise from replacing market energy by energy generated through incineration, and primary copper by the recovered materials. It is assumed that incineration emissions are the same regardless of which of three materials is incinerated. In reality, incinerating bio-based materials results in biogenic carbon emissions which will not impact the climate change category and therefore the impacts from generation 2 incineration could potentially be lower than generation 1.

Figure 28: Comparison between climate impacts of generation 1 and 2 dashboards with end-of-life recycling and potential credits from substitution included.

Recycling the dashboard at end-of-life results in mixed impacts to climate change for bio-PC and PEF. The potential credits from material and energy substitution could offset those impacts easily. However, the recycling processes differ for bio-PC and PEF. PEF recycling is modelled as mechanical recycling based on ecoinvent data for recycling of plastic parts from WEEE and it includes the crushing and further separation of plastic flakes for reuse. Bio-PC recycling is modelled based on (Lee, Moon, & Kim, 2025) as chemical recycling via alcoholysis. The two are not completely comparable, as chemical recycling usually requires more resources but produces better quality material than mechanical recycling. Also, it is not totally clear whether bio-PC can undergo the same recycling process as fossil-PC. Chemical recycling possibilities for PEF were not considered.

In this case, credits arise from replacing primary plastic materials.

Comparison to benchmark

To see the impacts of switching from fossil PC to bio-based PC or PEF, a comparison was made. Figure 29 shows the generation 1 dashboard made with fossil PC set to 1 and the generation 2 bio-PC and PEF alternatives are presented as relative to it. The comparison only includes manufacturing of the dashboard.

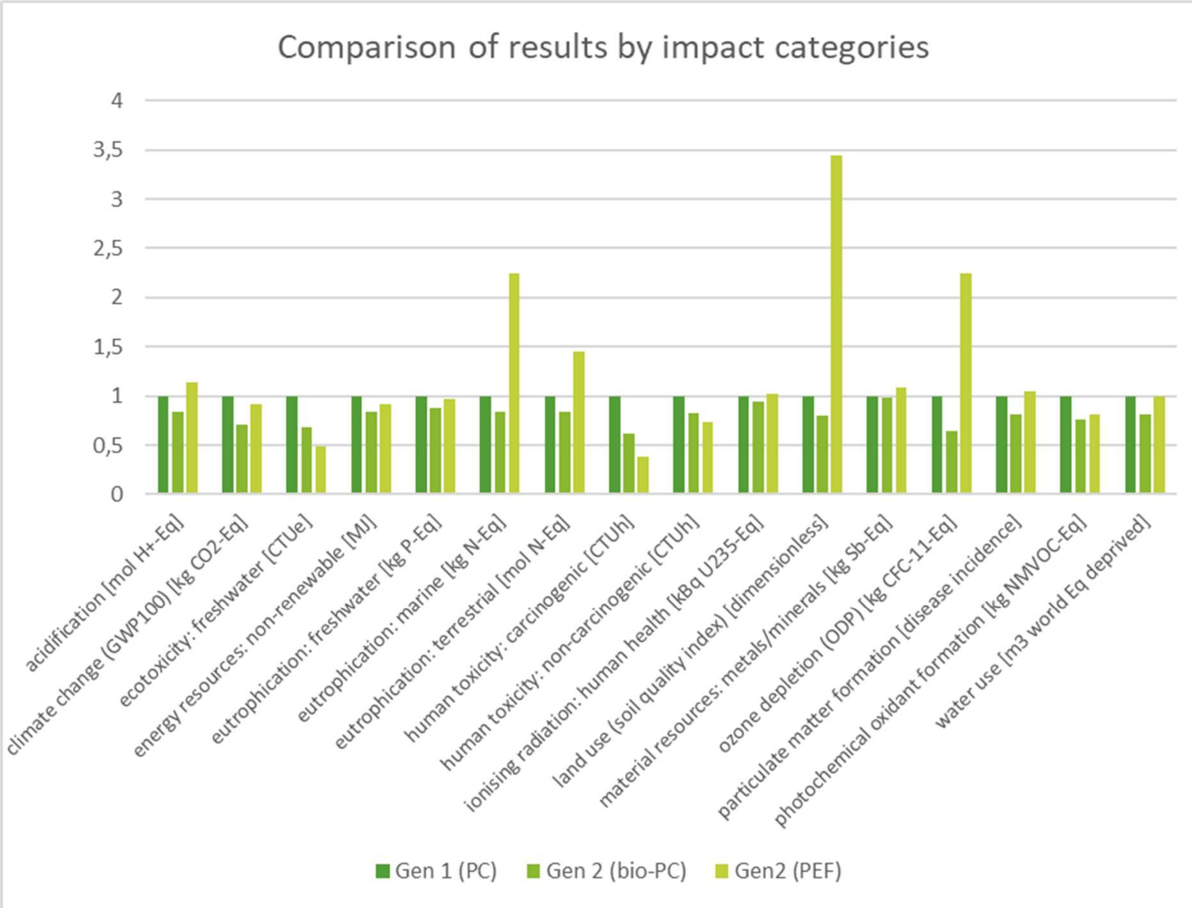


Figure 29: Comparison of generation 1 and generation 2 dashboard manufacturing, all impact categories.

As stated before, PEF exhibits pronounced impacts in ozone depletion, land use, and marine eutrophication, whereas bio-PC demonstrates comparatively lower impacts in these areas. Compared to fossil PC, both alternatives show positive impacts in some categories. PEF and bio-PC are both made from plant-based materials and therefore exhibit higher impacts in land use category.

However, data gaps exist for ecotoxicityicity and human toxicity impacts, especially for PEF, and the bio-PC results are extrapolated from fossil PC data, which may affect the reliability of the comparison. This suggests the need for caution in interpreting the environmental trade-offs between these materials. As mentioned before, environmental trade-offs in eutrophication and water consumptions are to be expected when using bio-based feedstock. Impacts on land use are also often higher for bio-based materials as the crops need to be grown which requires the use of land. Therefore, it may be that bio-PC has potentially as high impacts as PEF in eutrophication and land use as they both derive from bio-based materials.

Based on these calculations, it cannot be explicitly said, which material is the best environmentally.

4.3.5. Conclusions

The findings from Pilot 2.3 highlight both the potential and the limitations of transitioning from fossil-based PC to bio-PC and PEF for dashboard manufacturing. While both bio-based alternatives offer potential environmental advantages over fossil PC, such as reduced impacts in specific categories, the results are nuanced by significant data gaps—particularly for ecotoxicityicity and human toxicity impacts in PEF, and for environmental impacts beyond carbon footprint in bio-PC. The reliance on extrapolated data for bio-PC and the absence of comprehensive reference data for PEF introduce uncertainty into the comparative analysis.

End-of-life scenarios, including incineration and WEEE recycling, provide additional credits through energy and material substitution, but their full environmental implications require further detailed assessment. Overall, the study demonstrates that while bio-PC and PEF have the potential to reduce certain environmental burdens, a holistic evaluation of their life cycle impacts is constrained by current data availability, necessitating caution in drawing definitive conclusions and underscoring the need for more comprehensive and representative data for future assessments.

5. LCA results Case Study 3

5.1. Pilot 3.1a

5.1.1. Introduction

Pilot 3.1a, led by IFAT, aims to develop a point-of-care test kit for in-vitro diagnostics. The test kit measures C-peptide and creatinine levels in order to provide an extended view of metabolic disorders. The test kit is a disposable device that collects and analyses the sample and, by communicating with a smartphone, provides results directly.

The prototype focuses on additive manufacturing and environmentally informed material selection to minimise the impacts per unit. In order to meet the planned timeline and prioritising having a functional version in place by the end of the project, this pilot decided to co-develop two versions of the device in parallel: the functional version (which focuses on functionality) and the sustainable version (which is more ambitious in its environmental performance). In Gen 3 of the prototype, both versions are combined based on its technological feasibility. Therefore, the sustainable version has been chosen as the reference, but both versions are presented and compared in the interpretation section.

This pilot has received contributions from CBM, URV, CAN, CSEM, SCR, VTT, TER, STS, MEDUG, TAU, and CSIC.

5.1.2. Scope of the Study

This LCA is cradle-to-grave, meaning that it covers all relevant life cycle phases from raw materials acquisition to End-of-Life (EoL). The scope was set at cradle-to-grave however in order to better capture impacts and trade-offs further down the line.

As commented above, the baseline model is the so-called functional version, in which functionality has been at times prioritised over sustainability in order to achieve a working prototype. An alternative version, the sustainable version, has been co-developed where further eco-design choices have been taken showing the potential of the prototype. This model is also covered in the present LCA as an additional scenario.

In this LCA no particular cut-off rule has been followed, and the main inclusion criteria has been data availability. A more detailed explanation of the included processes is given in the following section.

The EoL allocation approach chosen has been 0/100, which includes credits for avoided production of the recycled elements. These credits are presented separately in order to avoid confusion.

As commented in the introduction, the EF3.1 methodology is used for the calculation of midpoint impact indicators. The analysis will be focused on a selected list of relevant indicators.

5.1.3. Life Cycle Inventory

Functional version

The metabolic test developed in this pilot consists mainly of a printed electronics strip that connects the various components, the sensing area and the near-field communication (NFC) antenna included in its layout for the communication with the smartphone. The core component mounted on it is the ASIC chip. Sample collection is done through the Lateral Flow Strips (LFS) that are attached to the conductive tracks. Finally, all is enclosed by a 3D printed housing that protects the electronics leaving an opening over the LFS for the sample.

The strip is printed on PET film substrate and modelled as such. The conductive tracks use silver ink modelled using a modified Ecoinvent dataset for metallization paste. Data on the screen printing process is derived from primary data from other pilots, except from the curing energy needs, which are based on parameters providing by CSIC. The BoM and amounts for the printed strip is derived from the dimensions and information provided by IFAT and partners. The ink amount used in the printing is derived from the layout documents provided by CSEM. This includes additional layers i.e. the dielectric layer and the electrodes.

The energy management of the device is provided by the printed supercapacitor developed by TAU. The supercapacitor also has two versions (functional and sustainable). Both the BoM and the manufacturing process for the supercapacitor have been modelled following (Kattainen, 2025).

The LFS has been modelled based on a BoM provided by URV.

The housing is made via 3D printing using polylactic acid (PLA) as the base material. The mass required has been derived from the dimensions of the housing provided by CSEM and the 3D printing energy is based on literature (see Section 3.3.3 for a more detailed explanation).

The ASIC is modelled using the Open IC model from Sphera LCA for Experts and the main modelling parameters (i.e. die size, package size, technology node) have been provided by IFAG.

Transport covers upstream transport (i.e. transport of parts to assembly), based on the current locations of the partners and the sent part weights. Since currently the products are not in the market, no transport to consumer is included. This phase should therefore be considered as provisional modelling and not yet representative of a real-life scenario.

The use phase is modelled based on the storage capacity of the supercapacitor. The energy is taken from the smartphone, but it is still allocated to the use of this device.

Since this is a disposable device to be used at home, it is assumed to be disposed of in the regular bin and thus end up in the municipal waste stream and ultimately incinerated. The incineration process is modelled using generic datasets representing the different materials and parts contained in the pilot e.g. plastic, electronics etc.

Sustainable version

The sustainable version introduces several changes in the product design. Starting with the printed strip in which the substrate is paper instead of plastic and the conductive tracks are printed using copper-based ink instead of silver ink.

Furthermore, the ASIC chip is not a full packaged chip but instead a bare die mounted via flip chip bonding directly on the paper.

As mentioned, the supercapacitor also has a different, more compact design, which saves space and material.

The rest of the life cycle phases are modelled in the same way, with only minor adaptations to account for differences in weight and material content.

5.1.4. Life Cycle Impact Assessment and scenario analysis

Figure 30 shows the environmental impacts share for the full life cycle of Pilot 3.1a. As expected for a disposable, low energy product, production phase is responsible for almost all environmental impacts across the categories analysed.

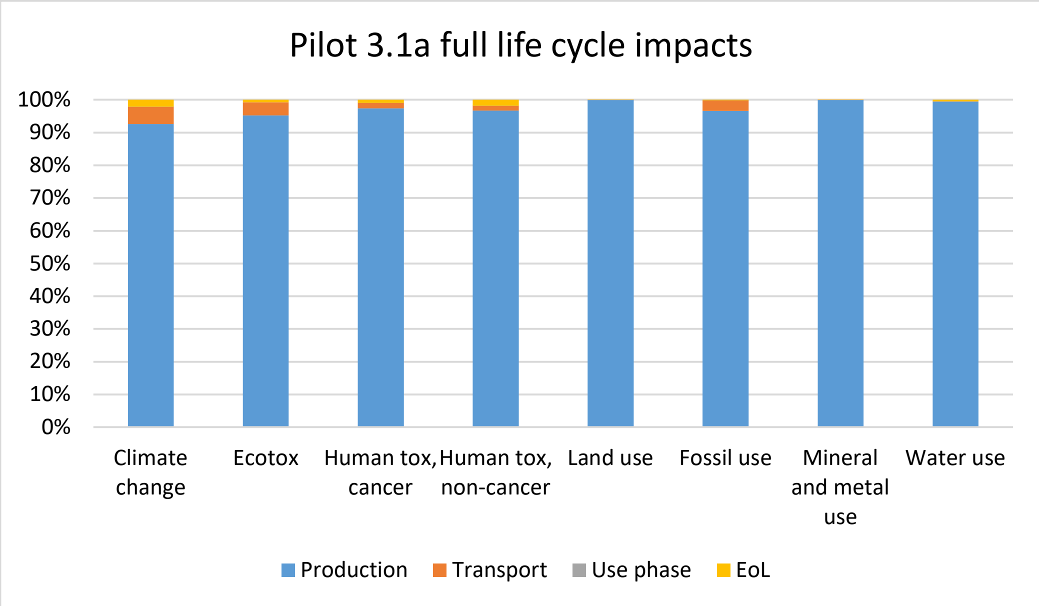


Figure 30: Contribution analysis for selected impact categories (EF3.1) for Pilot 3.1a for a single test, divided by life cycle phases.

Figure 31 provides a closer look at the production impacts of the prototype. It shows how the production impacts are driven by various parts. Firstly, the silver conductive ink used for the tracks is one of the main drivers of impacts, being the main lead for human toxicity and mineral and metal use. The Lateral Flow strips also show a significant contribution specially for land use, while the printing process itself drives water use. The full ASIC chip also has a relevant contribution specially for climate change (~20%) and fossil use (15%). The housing manufacturing is the main driver for ecotoxicity, mostly due to the increased ecotoxicity impacts from bioplastics (PLA for Gen 3). Lastly, the supercapacitor also shows to be relevant for some indicators, such as fossil and land use.

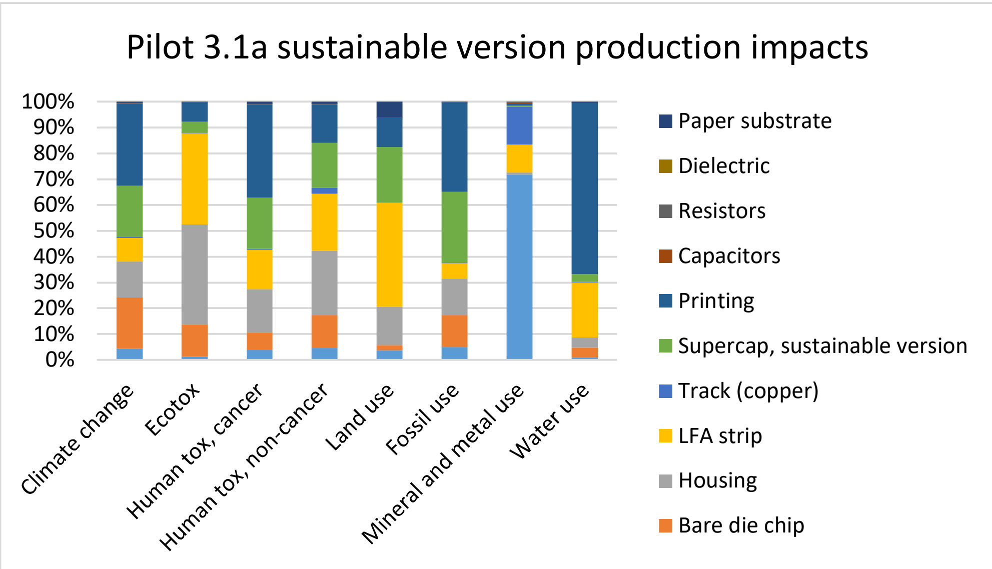


Figure 31: Pilot 3.1a production impacts share, divided by part.

Functional vs sustainable version

Above the main environmental hotspots for the functional version of the Pilot 3.1a prototype have been identified. As commented earlier, many of these are tackled in the sustainable version. A comparison of the production of both for climate change is shown in Figure 32. The biggest reduction is achieved by replacing the silver ink for copper ink. Furthermore, the substrate replacement, the smaller supercapacitor and the bare die mounting of the chip all contribute with smaller reductions in the manufacturing emissions. The total reduction amounts to 30%.

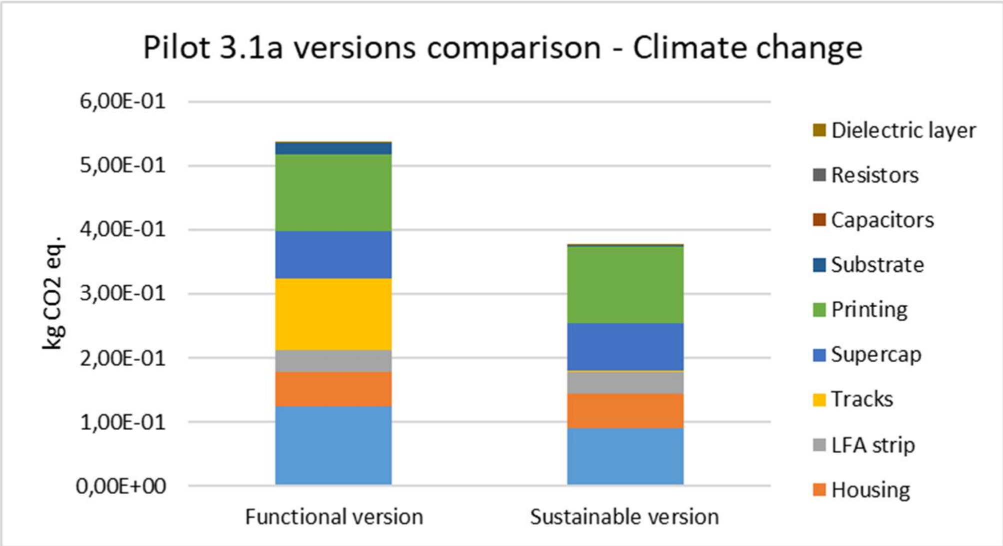


Figure 32: Climate change (EF3.1) comparison for the production of the functional and the sustainable versions of Pilot 3.1a, divided by part.

Mineral and metal use shows a much sharper drop (see Figure 33). As commented in the Section 3.3.4, this indicator is mostly driven by the consumption of key metals and minerals like gold and silver. By replacing silver for copper, a reduction of 96% can be reached (substrate substitution also contributes to this reduction although comparatively less).

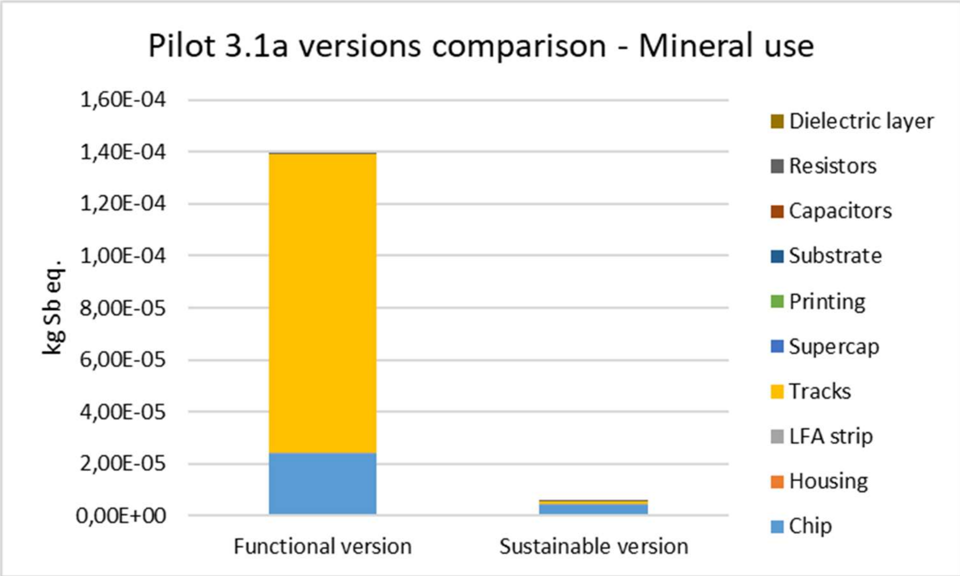


Figure 33: Comparison of mineral use (EF3.1) between the functional and sustainable versions of Pilot 3.1a, divided into parts.

Finally, Figure 34 shows the comparison for ecotoxicity. Here a reduction of 25% is achieved mostly by the replacement of the silver ink for copper ink. The new substrate and the bare die mounting also provide a marginal decrease as well.

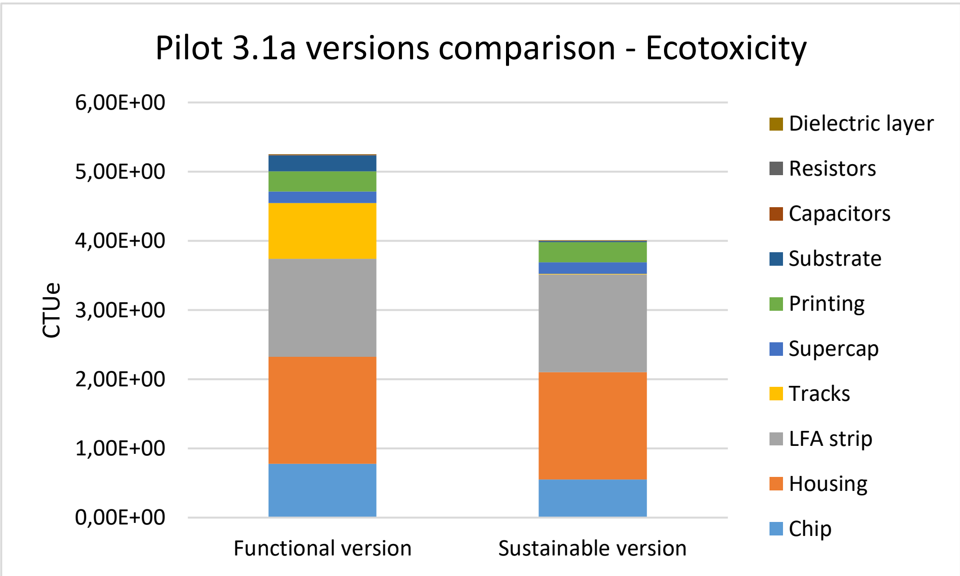


Figure 34: Ecotoxicityicity (EF3.1) comparison of the functional and sustainable versions of Pilot 3.1a, divided into parts.

5.1.5. Conclusions

The production of the prototype is what dominates the impacts of its entire lifecycle. Some of the identified hotspots were already tackled in the co-developed sustainable version of the device. The most relevant and the most effective in terms of impact reduction was the use of non-silver based conductive inks for the label layout, in this case copper. The other relevant hotspot, the ASIC chip, shows small potential reduction by the bare die integration. Ultimately the advantages of such a design depend on the type of packaging that the reference uses. An aspect that remains to be improved is the housing. While bioplastics are potentially interesting alternatives to other materials, the possibility of using recycled material could be considered to further decrease the product impact.

For an insight of potential indirect benefits of this solution, please refer to the carbon handprint in Section 6.2.

5.2. Pilot 3.1b

5.2.1. Introduction

Pilot 3.1b aims to develop a multisensing medical wearable device with the aim of constant monitoring of a series of indicators from sweat with the overarching goal of early diagnosis and proper management of diabetes.

The device is composed by three main parts: a disposable patch that collects the sweat and is in charge of the sensing (subsequent generations during development employ different techniques, more on this in following sections), a reusable band for fixing the patch and the reader and the also reusable reader that contains all electronics.

The collected data is then sent to a portal that uses AI to present the user not only with the results of the analysis but also with recommendations on lifestyle and diet adapted constantly to the sensor readings.

5.2.2. Scope of the study

This LCA is cradle-to-grave, meaning that it covers all relevant life cycle phases from raw materials acquisition to End-of-Life (EoL). However, the scope was set at cradle-to-grave in order to better capture impacts and trade-offs further down the line and fully reflect a realistic use case when it comes to the reusable and disposable parts. The functional unit has been set to a month worth of use of the sampling patch.

This LCA uses as its baseline the latest iteration of the device for which there is sufficient data available. In the sensitivity analysis section, the various generations will be compared to bring attention to the eco-design work been done within the development process.

Even though this pilot uses AI for the support of the app that is part of the use of the pilot, the required infrastructure and energy use are not part of the scope since the same data centers and servers are likely to support many units and thus the per-user impact is likely negligible.

In this LCA no particular cut-off rule has been followed, and the main inclusion criteria has been data availability. A more detailed explanation of the included processes is given in the following section.

The EoL allocation approach chosen has been 0/100, which includes credits for avoided production of the recycled elements. These credits are presented separately in order to avoid confusion.

As commented in the introduction, the EF3.1 methodology is used for the calculation of midpoint impact indicators. The analysis will be focused on a selected list of relevant indicators.

5.2.3. Life cycle inventory

Since the design of both versions is substantially different, they will be explained separately in the following sub-sections.

Transport was modelled based on the location of the contributing partners and it does not include transport to customer.

Use phase impacts are based on the battery capacity of the sensor reader device.

EoL modelling in this device is modelled differently for each part: the disposable part, since it is expected to be used in a non-clinical context, is assumed to be thrown with the municipal waste. The reusable part (i.e. the DM reader) is assumed to be properly disposed of as WEEE and recycled through that pathway.

Baseline – Generation 3

The device is composed of three parts: the DM reader, the sweat sampling patch and the wristband. The core concept of the device is to gather sweat directly from the skin and use visual detection from the DM reader to analyse the sample and produce the results. This way, no electrodes are required.

The sensor reador, also called DM reader, is composed by a housing made of 3D printed PLA. The PLA is modelled using generic dataset for US sourced, corn-based PLA while 3D printing energy needs are based on the same sources used for Pilot 1.3 (see Section 3.3.3). The optical window is made from recycled PMMA and is modelled using a generic dataset for undifferentiated secondary plastic. Lastly, the DM reader includes a fully mounted PCBA made out of conventional, off-the-shelf surface-mount device (SMD) components needed for the reading and processing of the data and a single-cell li-ion battery to power it. The PCBA inside and all its electronics have been modelled based on data provided by ONA and using generic datasets from the Sphera database.

The sweat sampling patch is composed of several layers of materials that are in charge of collecting, keeping and displaying the sweat for its inspection by the DM reader. The closest layer to the skin is a salt impregnated substrate modelled as nonwoven polyester for textile. The sweat metering layer is modelled based on the material composition provided by ONA. Both the interrogation chamber and the reflecting bed are modelled using polyester as a proxy for hydrophilic films. The skin adhesive tape is modelled based on material data given by ONA. Finally, the patch aligner is modelled as rigid nylon.

The wristband is modelled as TPU, following material data provided by ONA. Figure 35 shows a diagram of the product’s architecture.

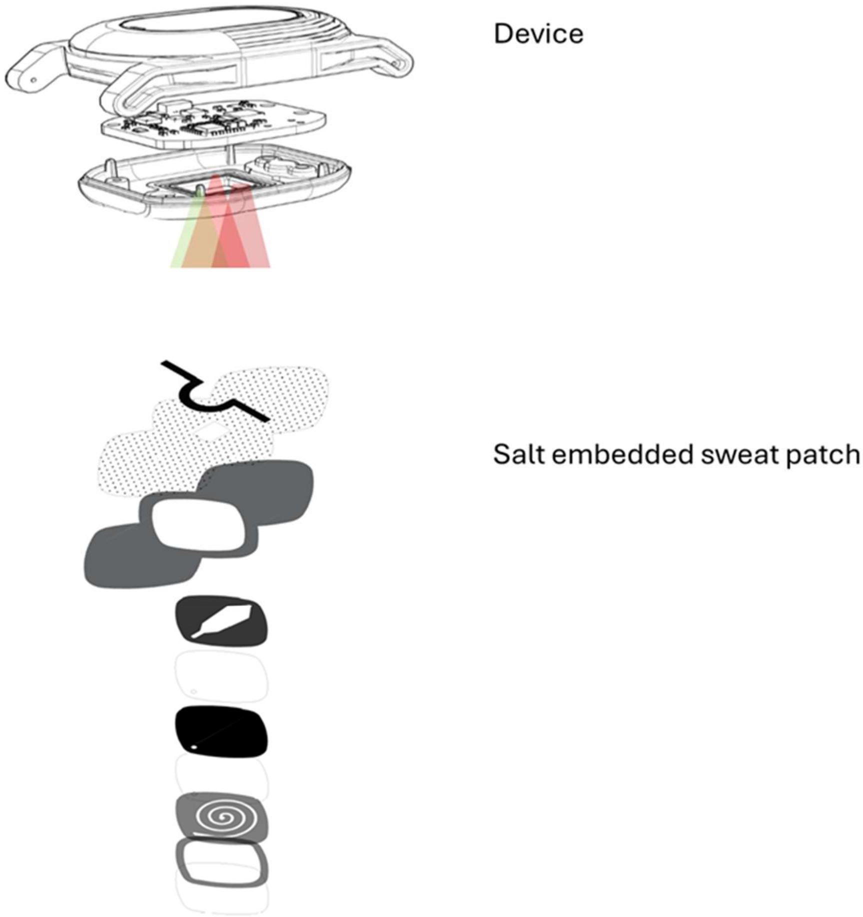


Figure 35: Explosion diagram of Generation 3 device in Pilot 3.1b

Generation 2

Unlike the baseline version, generation 2 represents an earlier iteration of the device. The main difference is that the sensing work in this version is done using printed electrodes in direct contact with the sweat sampling layers. For the most part the sweat sampling parts are basically the same (insofar this version still needs to collect and direct sweat). The particularities of this design are: firstly, this version includes an additional layer of printed sensor electrodes and secondly, that the DM reader gets the data directly from connecting to the electrodes as opposed to using a transparent window and a photonic sensor to visually detect the sweat.

The printed electrodes are modelled based on material composition data shared by ONA. The electrodes are printed on polyester substrates and use mostly copper conductive inks. The energy used in the printing process including ink curing is based on process parameters provided by CSIC.

The DM reader in this case is fairly similar to the final version, except for not needing the PMMA window. For the comparison presented below, the same DM reader model has been used for both versions.

5.2.4. Life Cycle Impact Assessment and scenario analysis

The functional unit is set to a month worth of using the smart patch for continuous monitoring. The patch needs to be changed once every 4 hours approximately, which means that for a month around 120 patches will be used. It is assumed that in that period a single reader is needed, although in practice it is bound to last much longer. Figure 36 shows the impacts share for a full month of use.

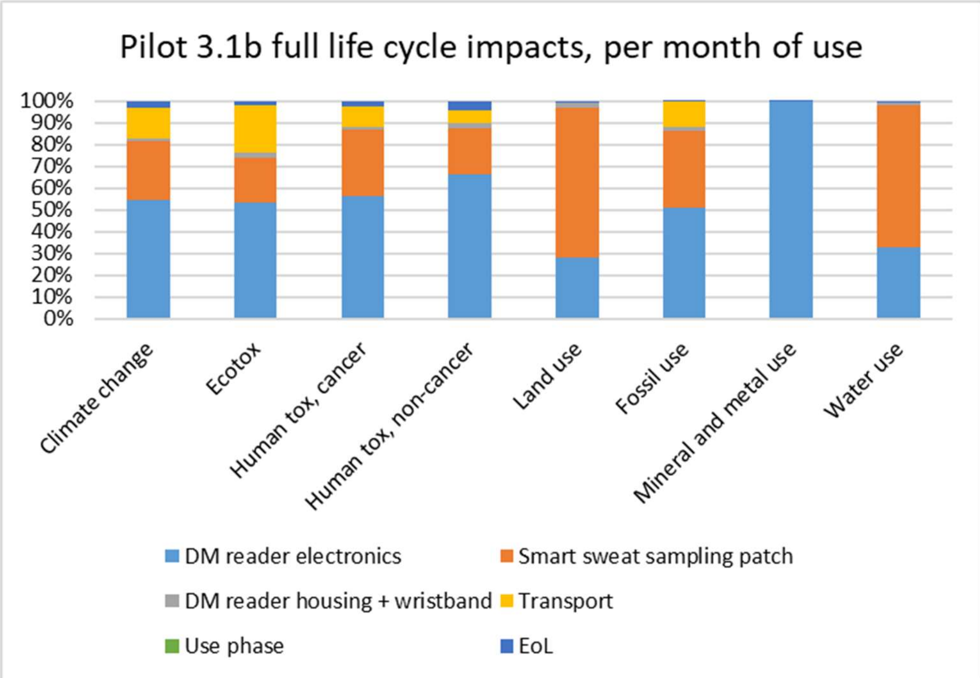


Figure 36: Full life cycle impacts for Pilot 3.1b for a full month of use, divided by parts and life cycle phases.

Despite only requiring one unit, the DM reader is the main driver for most of the indicators under analysis. The next main contributor are the disposable patches, which take up around 30% of the impact in most indicators. The only exceptions are land use and water use, in which the patches are the main driver, and mineral resource use, which is majorly linked to the DM reader electronics.

In Figure 37, the impact share for a single unit of the disposable patch can be seen. The rigid piece of nylon is driving most impacts, followed by the layer closer to the skin which is the salt impregnated layer (modelled as polyester).

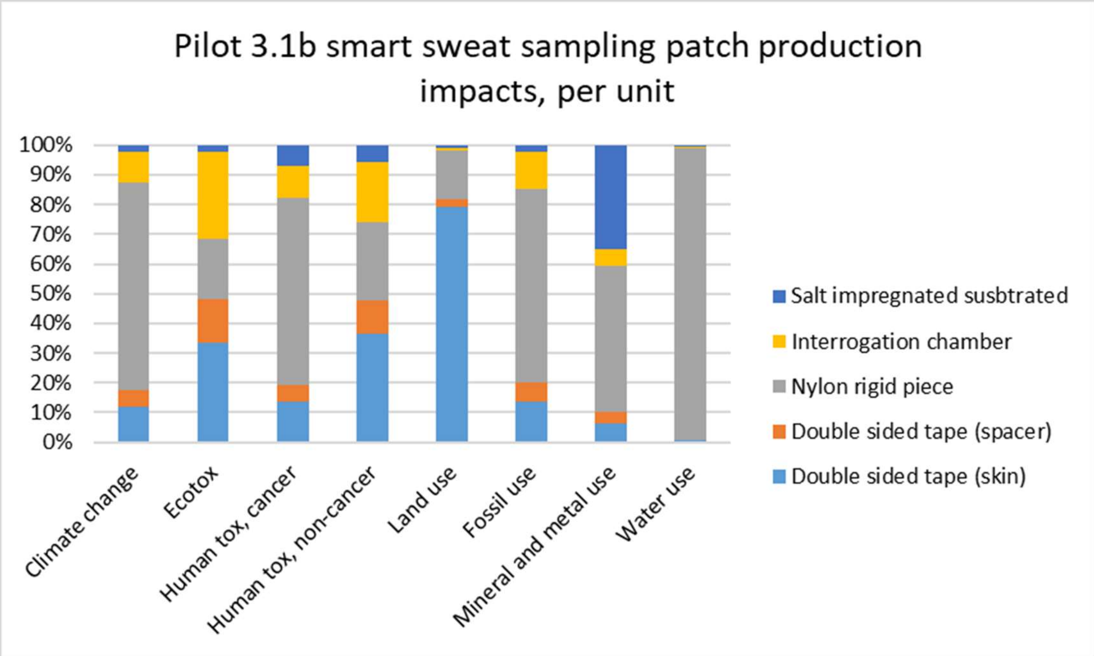


Figure 37: Sampling patch production impacts contribution, divided by parts.

Generations comparison

As commented in the inventory section, a previous iteration of the device employed printed copper electrodes for connectivity and sweat analysis instead of visual recognition. Figure 38 shows the comparison of that version to the final version, for one unit of the disposable patch. The impacts are divided into contributors: sampling structure, electrodes and manufacturing. The redesign that does away with the electrodes achieves a reduction of around 28 g CO_2 eq. per patch which adds up to above 3 kg CO_2 eq. per month. Comparatively, the textile layers and rigid parts in charge of the sweat collection have a lower impact than the electrodes.

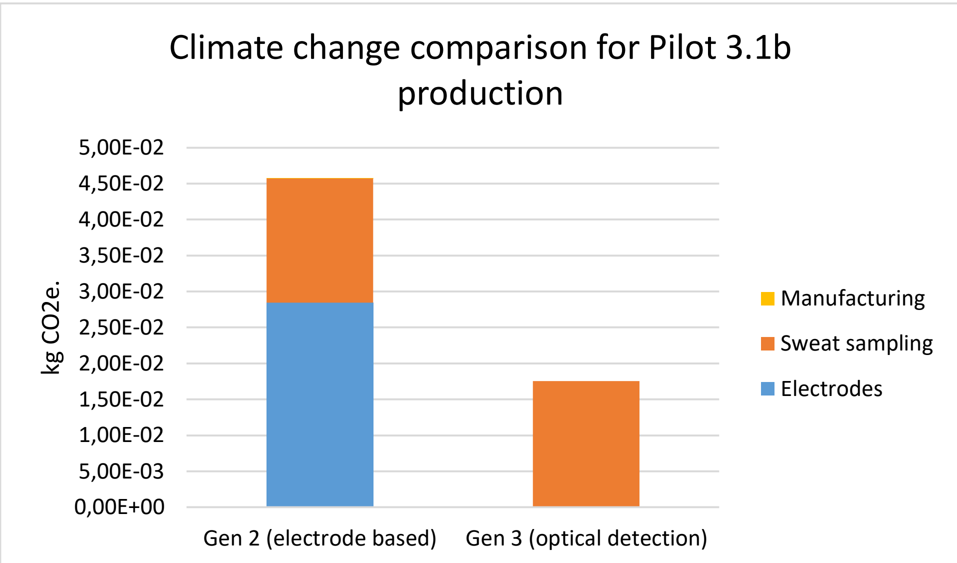


Figure 38: Climate change (EF3.1) comparison between generations 2 and 3 of Pilot 3.1b, production phase.

When looking at Figure 39, which display the same comparison for mineral use and ecotoxicityicity, it can be seen that the picture is the same. This showcases the significant advantages of the new design that does not require printed electrodes for sweat detection.

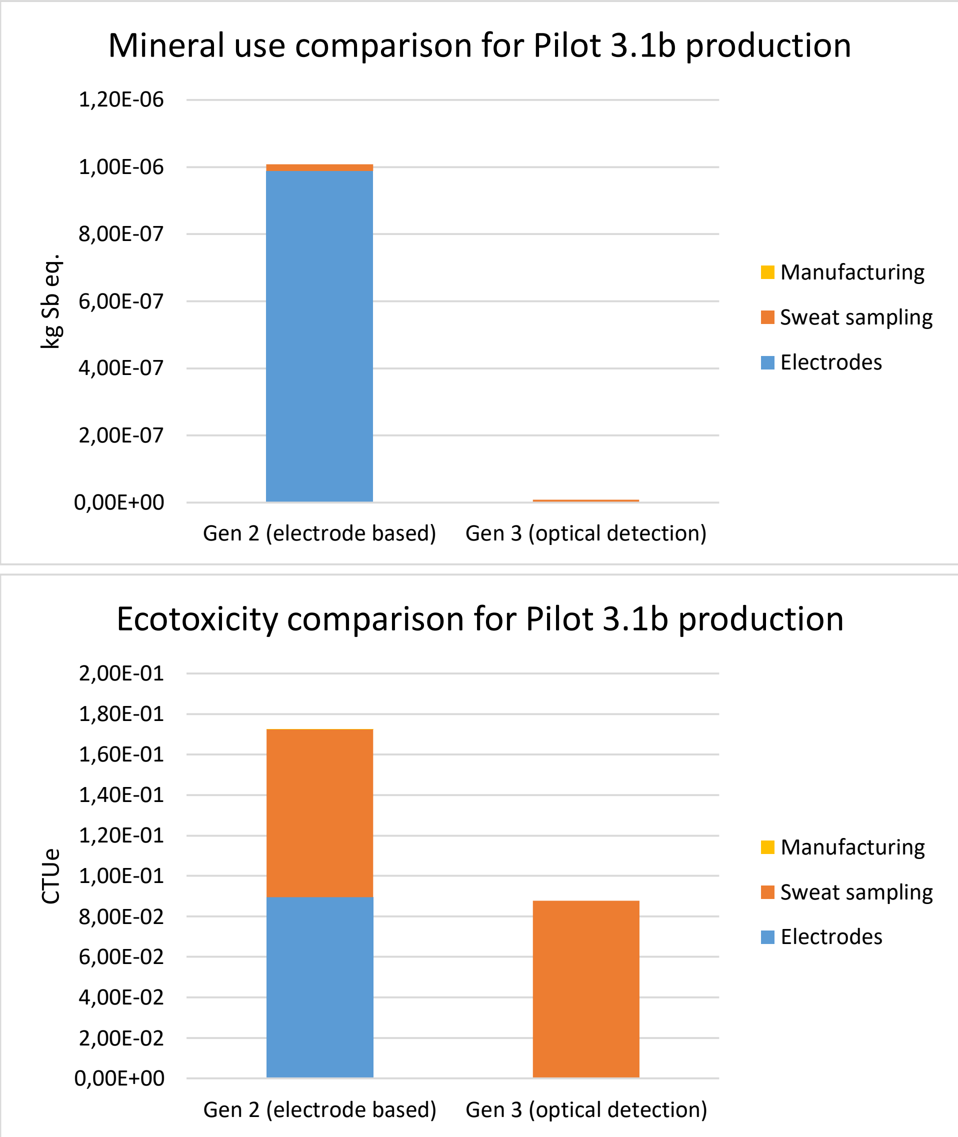


Figure 39: Mineral use and ecotoxicityicity comparison between generations 2 and 3 of Pilot 3.1b, production phase.

5.2.5. Conclusions

This pilot showcases that designs the potential of keeping most of electronics in the reusable parts of the product and rethinking the design not only for ameliorating the environmental hotspots but, wherever possible, to circumvent them. For the more electronics heavy parts, longevity and circularity strategies seem the best next step to avoid further impacts.

5.3.1. Introduction

Pilot 3.2 develops a smart hygiene product that adds sensing capabilities to incontinence products for adults. Its core is a single-use printed sensor label that is attached to the diaper itself, allowing for temperature, humidity, pH and enzyme sensing which transmits the gathered information to a smartphone in order to alert when a check or change is needed. In this way, too frequent manual checks are avoided, improving the user's comfort and optimizing care efficiency.

A reusable part contains most of the electronics and two version have been developed testing different connectivity options between the label and the reader.

5.3.2. Scope of the study

This LCA is cradle-to-grave, meaning that it covers all relevant life cycle phases from raw materials acquisition to End-of-Life (EoL). This has been chosen not only to capture potential trade-offs down the line but also to properly represent the actual use case scenario. The functional unit is set to be 1 month worth of use of the hygiene products.

As mentioned in the introduction, there is two versions of the device being developed in parallel: design A (where the disposable and the reusable parts are connected physically) and design B (in which the disposable and reusable parts connect wirelessly via NFC).

In this LCA, no particular cut-off rule has been followed, and the main inclusion criteria has been data availability. A more detailed explanation of the included processes is given in the following section.

The EoL allocation approach chosen has been 0/100, which includes credits for avoided production of the recycled elements. These credits are presented separately in order to avoid confusion.

As commented in the introduction, the EF3.1 methodology is used for the calculation of midpoint impact indicators. The analysis will be focused on a selected list of relevant indicators.

5.3.3. Life Cycle Inventory

The disposable sensor label contains four different sensors and conducting tracks that lead the sensor signals to the reader. The sensor label and its components are manufactured via additive manufacturing using various materials. Most of the circuitry in the sensor label is screen printed directly onto a paper substrate using functional inks, where silver is used for the conductive tracks. The lab-scale printing on sheets is done at RISE and upscaled R2R printing is done at BEN. The electrodes and the label are modelled based on material and process data provided by the responsible partners. Lastly, the assembly of sensor sticker components on to the label is done by a pick-and-place process, via robotic arms, by VTT and they provided an estimate on the energy use per label based on the machine specifications and process duration, data which is used for modelling its energy demand.

In its latest version (Gen 3), the transmitter is composed by a single round PCBA that performs both the readout and the transmission. This reader is built on conventional off-the-shelf electronics and on a conventional PCB. The transmitter board is modelled based on the BoM provided by CSEM and GUT.

The diaper itself is not covered by the scope since it does not differ from a regular diaper, and it remains the same across versions. It is to be noted that the reduction of needed changes due to the smart detection would eventually reduce the diaper use when compared to the current state of the art.

Transport covers upstream transport (i.e. transport of parts to assembly), based on the current locations of the partners and the sent part weights. Since currently the products are not in the market, no transport to consumer is included. This phase should therefore be considered as provisional modelling and not yet representative of a real-life scenario.

The use phase has been modelled differently for both versions since the sensors are powered differently, please refer to the sub-sections below for further details on each.

The EoL has been modelled based on data from (Nabavi-Pelesaraei, Mohammadkashi, Naderloo, Abbasi, & Chau, 2022) and represents typical medical waste treatment consisting mostly of disinfection and incineration. Since the product is to be used in a clinical context and will be contaminated with urine and/or faecal matter, it is assumed that properly medical EoL is the most likely scenario.

In the following sub-sections, the specific modelling differences between both versions of the design will be outlined. The rest of the life cycle phases remain unchanged and as described above.

Design A

In design A, the label and the reader connect via physical connectors. It has been modelled using a generic dataset for a conventional board-to-board connector. In this version, the label does not need any energy source of its own. In this version, the reader is also worn hanging from the diaper.

The sensors and the whole transmitter are powered by a battery in this case and thus the battery capacity is used as a reference for the energy consumption. Based on experience by GUT with similar devices, the battery is assumed to need recharging once every month.

Design B

In design B, the label connects wirelessly directly to the mobile app. This means that the label has additional silver tracks on it in order to add an NFC antenna that can send the signal out. In this case, the readout from the sensors is done directly on the label via an ASIC chip provided by Infineon as a bare die, which is integrated directly on the paper sensor label using anisotropic conductive adhesive by RISE. The transmitter is still needed in this design but it can connect wirelessly to the label and gather the readouts for transmission.

Similarly to design A, the transmitter is also powered by a battery and it feeds the label via NFC energy harvesting. Although not in the final design, if this option were not enough, a supercapacitor developed by TAU could also be included in the label (design B) as a rechargeable energy storage device. Thus, the supercapacitor's energy content has been used for a reference in the use phase modelling. Likewise, the life expectancy has been assumed to be of 1 year.

5.3.4. Life Cycle Impact Assessment and interpretation

For the presentation of the LCA results, the design A version is considered as the baseline. A comparison with design B is presented in the sensitivity analysis section.

Figure 40 shows the full life cycle impacts of a full month worth of use for the Pilot 3.2 design A device. The main assumption is that the diapers need to be changed every 8 hours, which equals 3 units used per day. This means 90 diapers in a month, 90 single-use sensor labels and, as a conservative assumption, a single reader unit reused continuously. The transmitter is assumed to last a full year so its full life cycle impacts are allocated here to their proportional part for a month (i.e. 0,08 units per month).

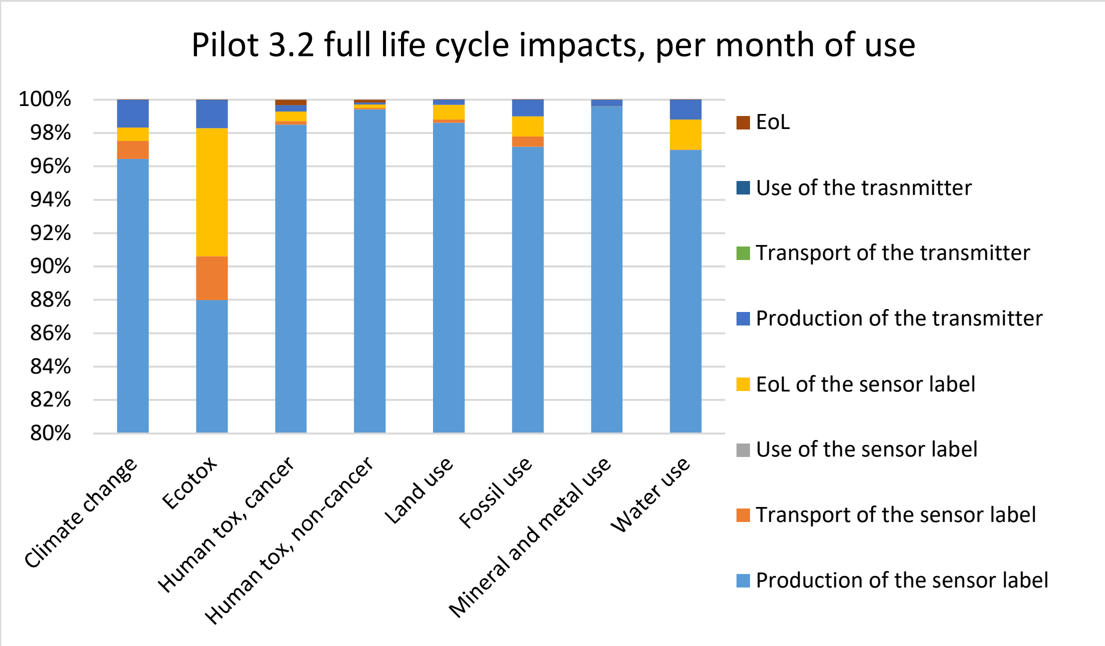


Figure 40: Full life cycle impact contributions for Pilot 3.2 (design A), divided into life cycle phases.

The graphic shows that, for almost all indicators assessed, the production of the sensor labels drives the impacts with a contribution usually above 80%. The only exception being ecotoxicityicity, in which the incineration of the labels at their disposal shows a significant contribution as well. Comparatively, the transmitter (i.e. the reusable part) shows a negligible contribution, since it can be reused well beyond the monthly period.

Figure 41 zooms in at the single use label production impacts. Here the picture gets slightly more complex. As shown, the printed label is the hotspot for most indicators, although the contribution level varies, and this is in turn driven by the production of the silver ink used for the conductive tracks. The second relevant contributor is the assembly process, modelled as explained earlier as electricity use. It is important to note that the assembly process is performed at a lab scale within the context of this project, and that the energy use is modelled based on assumptions since direct measurement was not possible.

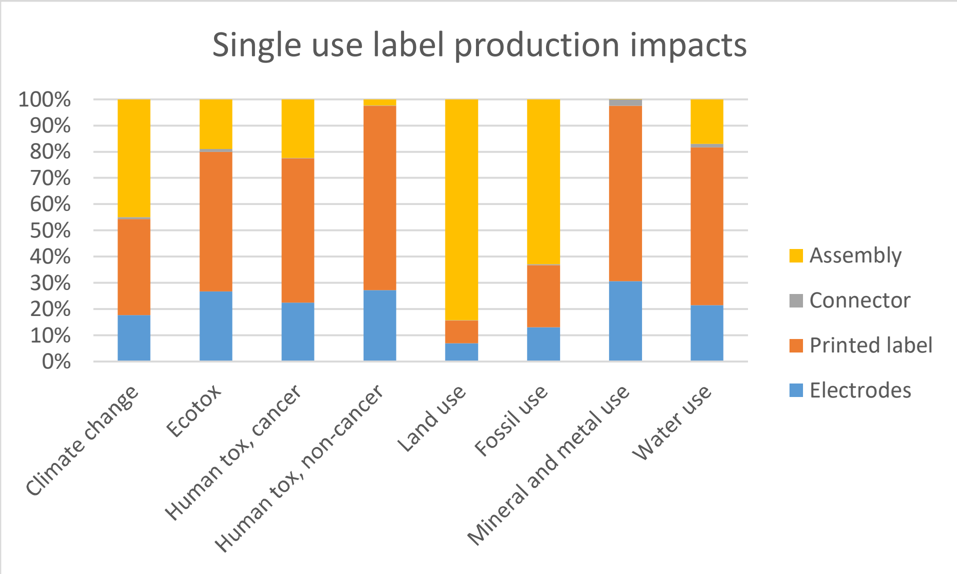


Figure 41: Disposable sensor label production impacts distribution, divided into parts.

What these graphics show is that, since this device has a disposable part and the renewal frequency can be potentially high, it becomes the main avenue for the uptick in environmental impacts. In the following section, this will be observed again when comparing both versions of the device.

Comparison of Gen 3 versions

As presented earlier, an alternative version of the device has been developed in parallel, which allows for wireless connection between the label and the transmitter. This has clear advantages first and foremost in terms of patient comfort, since design A with its direct physical connection requires that the transmitter remains hanging from the diaper at all times. This reduces the risk of accidental disconnection as well, preventing potential problems during use. Figure 42 shows, however, what the environmental effects are.

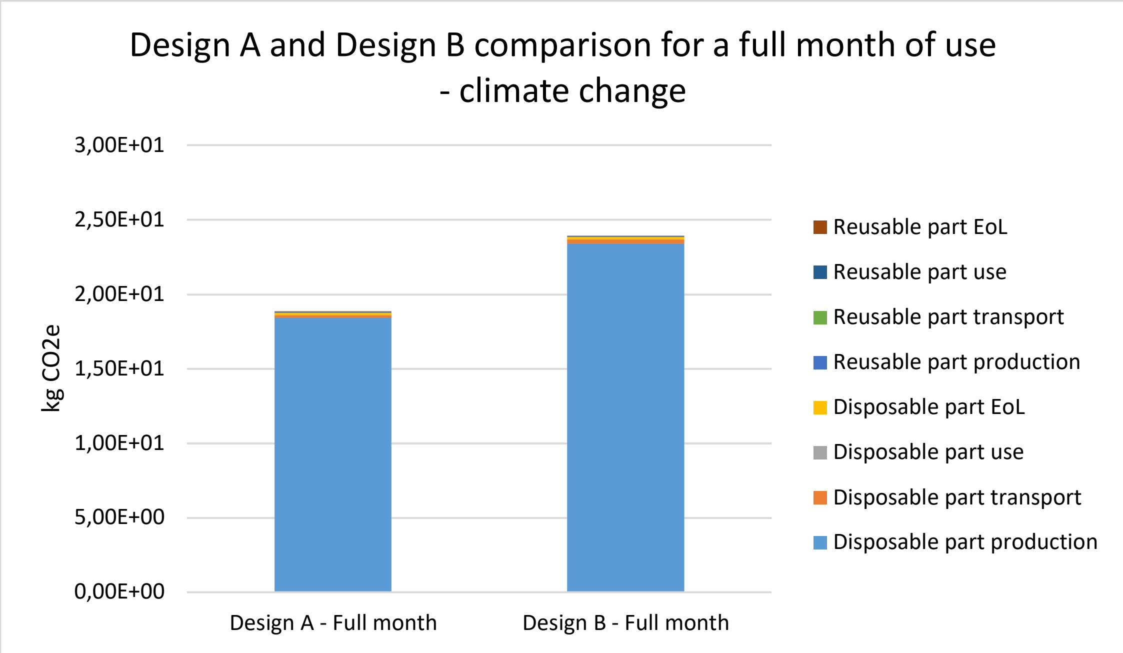


Figure 42: Climate change (EF3.1) comparison of both generation 3 versions of Pilot 3.2 for a full month of use.

The total impacts during a full month of use for both versions show that the wireless version (design B) has a higher impact: around 24 kg CO_2 eq. for the wireless version as opposed to 19 kg CO_2 eq. for the connector version, i.e. around 5 kg CO_2 eq. extra per month of use. In Figure 43 the causes of this can be seen at the label level.

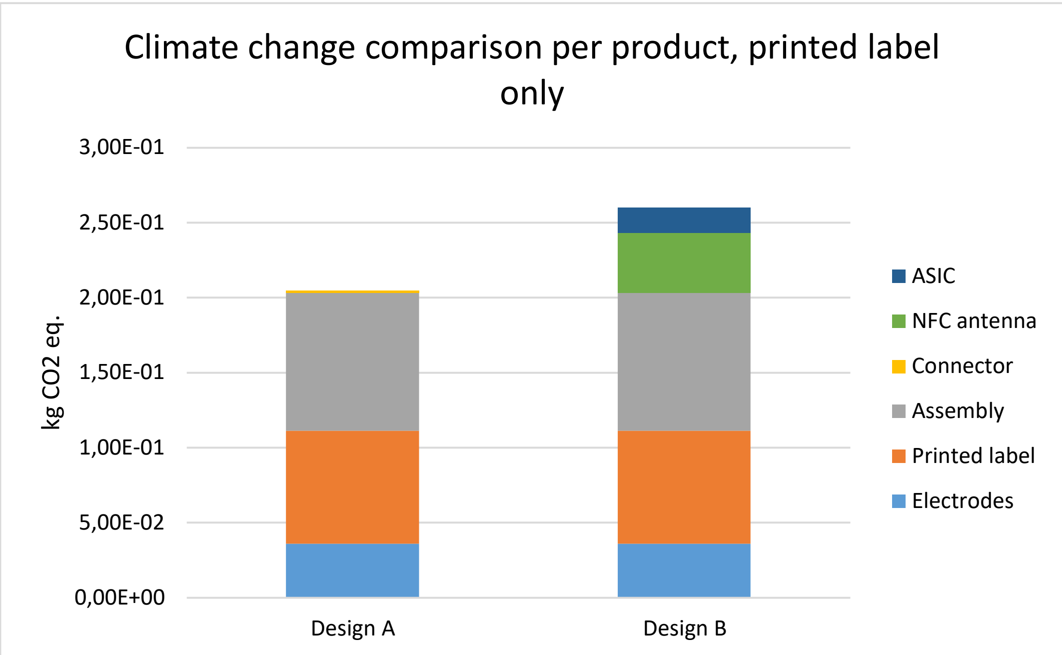


Figure 43: Climate change (EF3.1) comparison of both generation 3 versions of the disposable sensor label, per unit.

While the main layout of the label is pretty much the same in both versions, the wireless version requires some additional components to power and enable its connectivity. Firstly, it requires additional substrate area and silver ink to form the NFC antenna, being the main contributor to the impact increase. On top of that, the additional ASIC also adds some more production-related impact. A better overview of these impacts in provided in Figure 44, showing that mostly the silver ink used in the label, electrodes and NFC antenna (design B) is the main driver, alongside the robot arm assembly process energy.

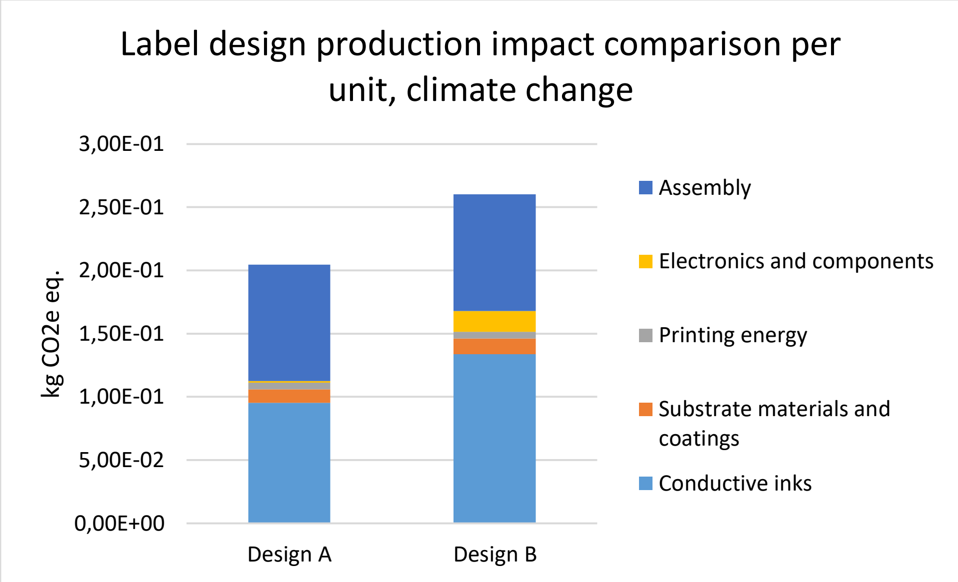


Figure 44: Climate change (EF3.1) comparison of both generation 3 versions of the disposable sensor label, per unit. Emissions broken down per input category instead of parts.

When looking at other indicators, the picture remains similar although the ranges change. Figure 45 shows the comparison for ecotoxicityicity for which design B also shows a higher impact, albeit not as different as in the case of climate change.

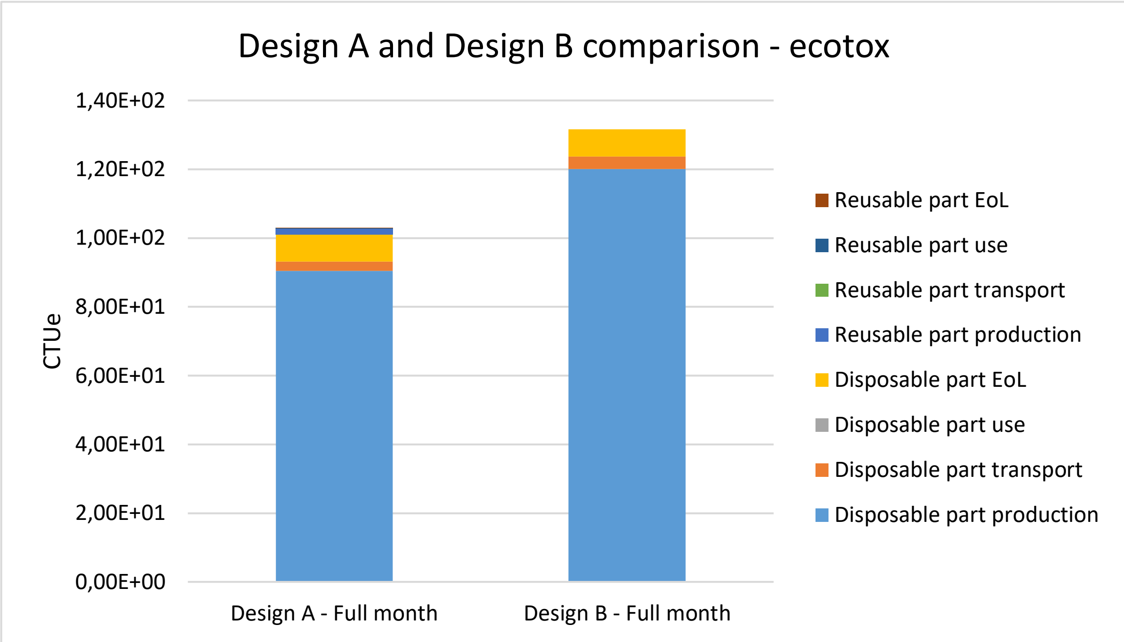


Figure 45: Ecotoxicityicity (EF3.1) comparison of both generation 3 versions, full month of use.

Metal and mineral use represents a relevant exception. In this case, due to the disproportionate contribution that the use of gold and silver has in this indicator (van Oers, Guinée, & Heijungs, 2020) and because the layouts are similar, the final impacts are also fairly comparable (see Figure 46).

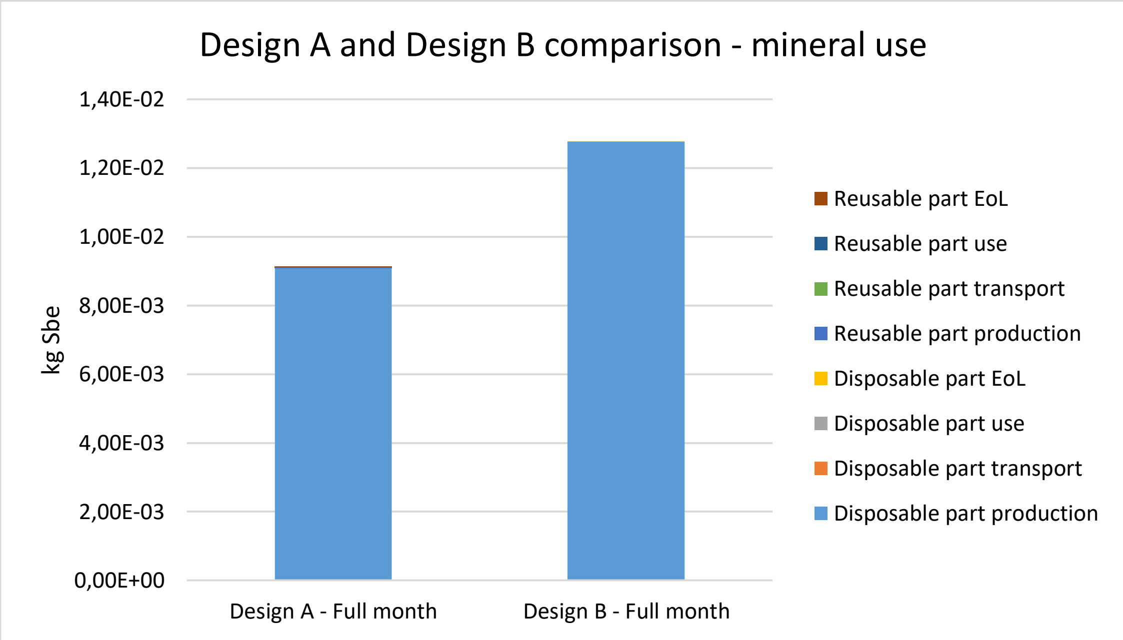


Figure 46: Mineral use (EF3.1) comparison for both versions of Pilot 3.2 generation 3, for a full month of use.

5.3.5. Conclusions

The results presented above show the benefits of modularity in single use products, allowing to shift environmental burden to the longer living parts and allowing for lower cumulative impact over use. However, the wireless version does provide other advantages such as comfort and ease of use, which are relevant for applications like senior citizens' hygiene. Although not achieved during the project, planned future developments include working on replacing silver ink with copper ink and a more monolithic integration of all sensors, removing the need for additional assembly efforts and simplifying manufacturing.

5.4. Pilot 3.3

5.4.1. Introduction

The pilot led by Infineon Technologies AG (Germany) aims to develop a point-of-care device for smart wound care. The device is designed for non-invasive monitoring of wound infections in order to enable personalized, needs-based dressing changes. By providing timely and reliable information on the wound status, the system is intended to support clinical decision-making and home care, and to reduce unnecessary interventions.

The overarching objective is to extend safe dressing wear times, thereby reducing the burden on the healthcare system (e.g. staff time, material use, and associated costs), while at the same time decreasing patient pain and discomfort and supporting undisturbed wound healing.

Current standard wound care largely relies on frequent, scheduled dressing changes to visually assess the wound and to prevent unnoticed infection. This approach is resource-intensive, can be painful for patients, and may disrupt the wound healing process. In contrast, the smart wound care system developed in this pilot uses a multisensing platform that combines resistive and electrochemical sensors to monitor key wound parameters such as temperature, pH, and uric acid. These indicators are associated with inflammatory processes and infection risk and can provide an early warning of complications without the need to remove the dressing.

By integrating this sensor system into wound dressings and linking it to appropriate data processing and communication tools, the pilot targets a more efficient, patient-centred, and environmentally improved wound management pathway compared to current practice.

During the project two theoretical versions have been developed using two strategies of circular economy: a simplified single use system with minimal components (reduce strategy, in graphics SU) and a partly reusable system (reuse strategy, in graphics RU). Within the project for the first generation a functional version of single components was developed. This represents the benchmark (BM) of the LCA study, the sustainable version represents sustainable improvements of such components (Sus).

This pilot has received contributions from ADD, BSN, EESY, GUT, IFAG, FHG, SWA, TNO, TUNE, TUUH, VULPES, and WUR.

5.4.2. Scope of the Study

This life cycle assessment is structured in two complementary parts:

- Cradle-to-gate: covering all impacts from raw material acquisition up to the manufacturing gate of the device and its main components. This perspective is used primarily to analyse and optimise single components and sub-systems of the design, and to better understand trade-offs between alternative material and process choices.
- Cradle-to-grave: covering all relevant life cycle stages from raw material acquisition through production, distribution and use, up to End-of-Life (EoL). This represents the main scope of the study and is used for the comparison of the different product generations and scenarios to identify the most sustainable design.

Two main benchmark prototype design variants, aligned with circular economy strategies, are assessed:

- Single-use “reduce” design: a minimalistic configuration aiming to reduce material use and complexity while retaining the required functionality.
- Partly reusable “reuse” design: a configuration in which the main electronics are designed to be reused across multiple dressing applications, thereby reducing the demand for new components over the device’s life.

Based on the results obtained for these benchmark designs, an additional configuration was co-developed with a stronger focus on eco-design at the level of individual components (e.g. material choices, design for disassembly, and improved end-of-life options). This configuration illustrates the improvement potential of the prototype and is included as an additional scenario in the LCA.

No explicit quantitative cut-off rule has been applied. Instead, data availability has been the main inclusion criterion. A detailed description of the included life cycle processes and any data gaps is provided in the following Life Cycle Inventory section.

The EoL allocation approach chosen has been 0/100, which includes credits for avoided production of the recycled elements. These credits are presented in the cradle-to-gate perspective negatively.

As described in the introduction, the EF 3.1 Life Cycle Impact Assessment (LCIA) method is used to calculate midpoint impact indicators. Within the main body of this report, the focus is on Climate Change (i.e. Global Warming Potential 100) and Material Resources as the key reported indicator.

5.4.3. Life Cycle Inventory

Baseline/Benchmark

The smart wound patch developed in this pilot consists of the following main elements:

- Flexible printed circuit board (PCB): to position the sensors within the wound exudate.

- Sensing system: selective electrodes for pH sensing and uric acid sensing, and a resistive temperature sensor.
- Read-out electronics: for receiving sensor signals and transmitting data to a base station or mobile phone.
- Dressing materials: including a wound contact layer and a secondary foam dressing for exudate management.

For both system approaches, the sensors are mounted on a flexible substrate, manufactured using two different manufacturing technologies:

For the additive technology, conductive tracks were printed with silver ink on a PET film substrate. The conductive silver tracks are modelled using a modified Ecoinvent dataset for metallization paste. For the subtractive technology, a copper foil on a thermoplastic polyurethane (TPU) substrate, was structured by etching to obtain the required pattern. The copper foil is modelled using an adapted Ecoinvent dataset for copper connection foil. In both cases, the flexible substrate is laminated using TPU. Primary process data for screen printing (additive) are provided by TNO, and for the subtractive etching process by FHG and WUR. The bill of materials (BoM) and quantities for the flexible PCBs are derived from geometric dimensions and technical information supplied by TNO, FHG and WUR.

The sensors themselves are modelled based on the BoM and sintering technology described in (Papamatthaiou, et al., 2020) with adaptations where necessary to align with the present prototype.

For the electronics both system architectures differ. For the “reduce” (single-use, SU) system all electronic components, including sensors and read-out electronics, are assumed to be directly integrated on flexible PCBs. This reflects a highly integrated, minimalistic design approach. For the “reuse” (partly reusable, RU) system, all electronic components except the sensors are integrated on a rigid PCB housed in a separate unit located next to the wound. This read-out unit is connected to the flexible sensor patch via a ZIF connector. The sensor patch itself remains flexible and disposable, while the read-out unit is designed for multiple uses.

The housing of the reusable read-out unit is produced via 3D printing using PLA as the base material. The required mass is derived from the housing dimensions provided by TNO, and the energy consumption for 3D printing is based on literature data (Kazmer, Peterson, Masato, Colon, & Krantz, 2022).

To manage sensor signals and transmit data, two integrated circuits (ICs) are used. (1) An ASIC for sensor management, which is modelled using primary data provided by IFAG, who developed the ASIC. And (2) a Bluetooth Low Energy (BLE) IC, which is a commercial off-the-shelf component, modelled using adapted primary ASIC data, scaled to the technology node and complexity of the BLE IC.

Other components required for the analogue front end (e.g. resistors, capacitors, passive and active discrete components) are modelled using appropriate Ecoinvent datasets. Owing to the higher system complexity of a rechargeable, reusable read-out unit, the single-use system is assumed to require fewer electronic components overall.

For both design variants, the device energy management is provided by a battery, as the system requires continuous monitoring. The battery is modelled using an appropriate Ecoinvent dataset for the relevant battery chemistry and capacity.

For the dressing material, the wound contact layer and the secondary foam dressing are modelled based on their material composition and mass, using adapted Ecoinvent datasets for the corresponding polymeric and foam materials. Material quantities are derived from design specifications (dimensions, thickness) provided by BSN.

Transport includes upstream transport, i.e. shipment of components and sub-assemblies from partners to the assembly location. Transport distances are based on the current locations of the partners and the and Ecoinvent market-based values. The transportation impact is included in the component impact. So far, no transport to the consumer or care facility is modelled, as the devices are not yet commercialised. The current transport modelling should therefore be regarded as provisional and not fully representative of a future real-world supply chain. However, for modelling the use case, transportation data for health care logistics are included.

For the reuse system, the use phase energy consumption is based on measurements of the developed demonstrator (charging frequency, operating time, and standby behaviour). For the single-use system, energy consumption is modelled assuming one full charging cycle of the battery over the reference use period corresponding to a single dressing application. Additionally, each dressing change in wound care is associated with a travel of a health care practitioner to the patient. This transport is modelled based on average community nurse distances of 1km and modelled with an eclectic as well as a petrol EURO 5 based car.

Given that the main wound care is assumed to take place in a home-care setting, all disposable parts (e.g. sensor patch, dressing materials, single-use electronics) are assumed to be discarded in regular household waste, entering the municipal solid waste stream and ultimately being incinerated. Incineration is modelled using generic Ecoinvent datasets representing the different material fractions present in the pilot system (e.g. plastics, electronics). For the reusable read-out unit, a generic waste stream for consumer electronics was modelled.

Sustainable Version

For the sustainable version includes several component-level design changes which have already been realised in prototype form. Since benchmark results show that reusing the main electronics already improves the overall system by avoiding the production and disposal of electronic components with every dressing change (see LCIA section), the sustainable scenario places particular emphasis on the single-use components, in particular the flexible sensor patch. Although benchmark results show that the reuse strategy is more sustainable the reduce strategy is still modelled in a sustainable version for comparison.

For both manufacturing routes of the sensor patch, dedicated sustainable variants were developed:

- **Subtractive manufacturing**: for the subtractive route, bio-based TPU substrates are used instead of conventional TPU. The environmental impact of the bio-based TPU is modelled using supplier-provided information, with only limited information provided in a total Global Warming Potential (GWP) value. Additionally, copper waste generated during production was recycled. The recycled content is included as accounting in the analysis at component level.
- **Additive manufacturing**: for the additive route, carbon-based conductive inks on paper-based substrates are modelled as alternatives to silver ink on PET as well as partly recycled PET with a recycling content of 50% and a silver ink using 100% secondary silver. The carbon ink is modelled based on its BoM. The paper substrate is modelled using adapted Ecoinvent datasets, cross-checked against CO_2 values provided by the supplier, the results being within a 10% error.

For the sensor IC (ASIC) of the sustainable version an ASIC manufactured with 100% renewable electricity was used.

For the reusable read-out unit, a recycling process is modelled at end-of-life, using generic datasets for the treatment of electronic equipment and associated material recovery. This reflects the design intention of recovering value from higher-impact, longer-lived components.

5.4.4. Life Cycle Impact Assessment and scenario analysis

For the presentation of the LCIA results, the single use benchmark (SU BM) version is considered as the baseline.

Baseline/Benchmark

When focusing on the cradle-to-gate perspective only, i.e. without considering the use phase and end-of-life, the benchmark reusable design (BM RU) exhibits the highest impacts for both climate change and material resource use, see Figure 47 and Figure 48. This is mainly due to its more complex architecture and the larger number of electronic and mechanical components in the reusable read-out unit (e.g. rigid PCB, housing, connectors).

In both additive and subtractive routes, the contribution analysis clearly shows that the electronics (including ICs and battery) dominate the cradle-to-gate impacts, while the dressing materials and flexible substrates play a comparatively smaller role. The higher component count and mass of the reusable unit therefore lead to greater manufacturing impacts per device when assessed in isolation.

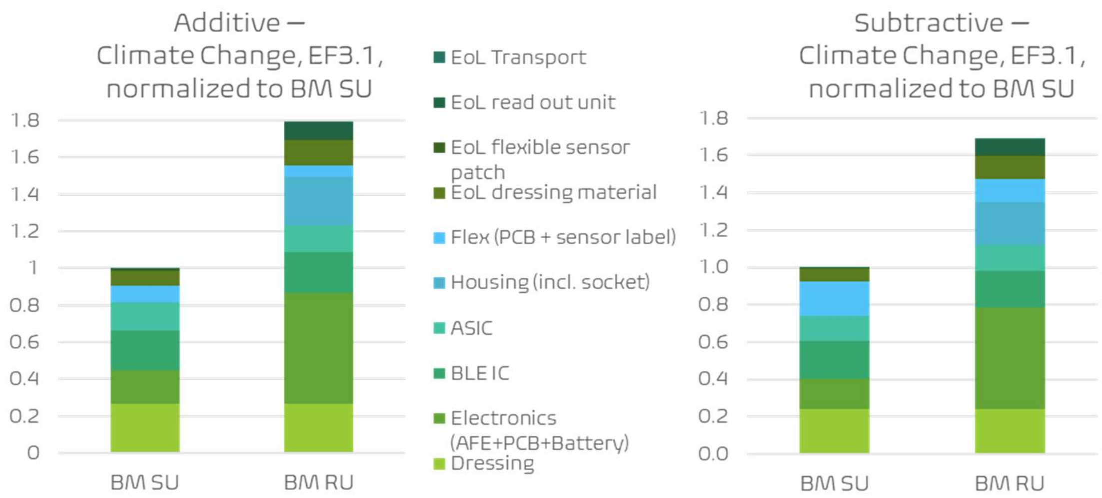


Figure 47: Cradle-to-gate climate change impacts (EF 3.1, midpoint, "Climate change"), normalized to the impact of the benchmark single-use configuration (BM SU). Results are shown for the additive and subtractive manufacturing routes and decomposed by single components for both the single-use (BM SU) and partly reusable (BM RU) designs.

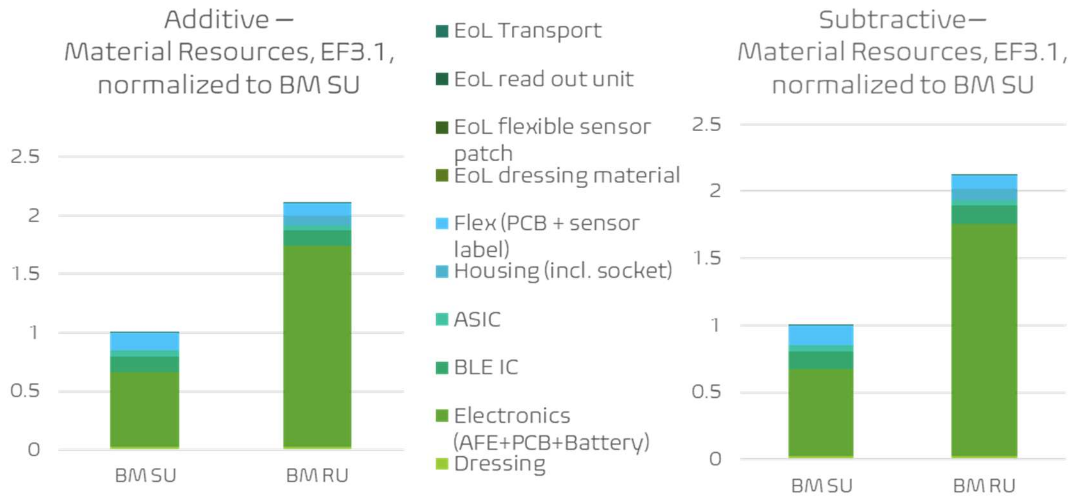


Figure 48: Cradle-to-gate material resource use impacts (EF 3.1, midpoint, "Material Resources"), normalized to the impact of the benchmark single-use configuration (BM SU). Results are shown for the additive and subtractive manufacturing routes, and decomposed by single components for both the single-use (BM SU) and partly reusable (BM RU) designs.

Sustainable Version

The sustainable design variants clearly demonstrate the effect of targeted eco-design measures at component level, see Figure 49 and Figure 50. A major improvement is achieved by switching to the sustainable versions of flexible PCBs.

For the additive route, replacing the PET/silver flex with a paper-based substrate and carbon ink leads to substantial reductions in both material resource use and climate change. Material resource use associated with the flex PCB is reduced by about 98%, while the climate change contribution of this part decreases by roughly 40% compared to the benchmark additive design.

For the subtractive route, introducing bio-based TPU and modelling recycling of copper in the flex PCB likewise yields significant savings. Material resource use for the flex PCB decreases by almost 80%, and the related climate change impact is reduced by around 30% relative to the benchmark subtractive configuration.

In addition, the introduction of a green-manufactured sensing IC (ASIC) reduces the climate change impact of this component by more than 50%, which has a noticeable effect at device level given the high contribution of electronics.

For end-of-life (EoL), the implementation of a recycling route for the reusable read-out unit leads to further reductions in the EoL impacts, as the environmental credits associated with recovered materials are considered. Especially, dominant for material resources, as shown in Figure 50.

Overall, the sustainable versions show that combining greener semiconductor manufacturing with low-impact flexible patches and improved end-of-life assumptions can substantially reduce cradle-to-gate impacts, while preserving the functional performance of the smart wound patch.

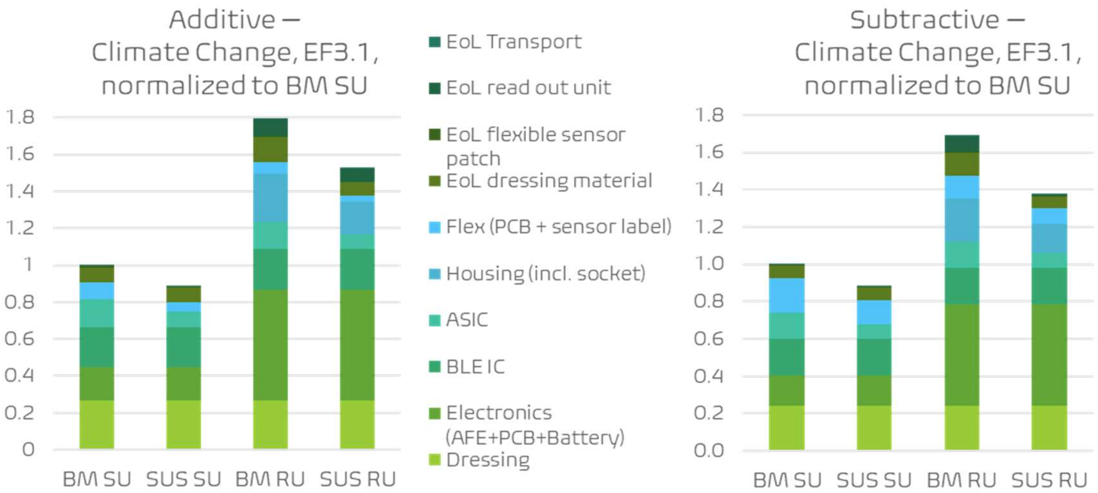


Figure 49: Benchmark and sustainable prototypes – cradle-to-gate climate change impacts (EF 3.1, midpoint, "Climate change"), normalized to the benchmark single-use configuration (BM SU). Results are shown for additive (left) and subtractive (right) manufacturing routes, and for benchmark single-use (BM SU), sustainable single-use (SUS SU), benchmark reusable (BM RU) and sustainable reusable (SUS RU) designs. Contributions are decomposed by single components.

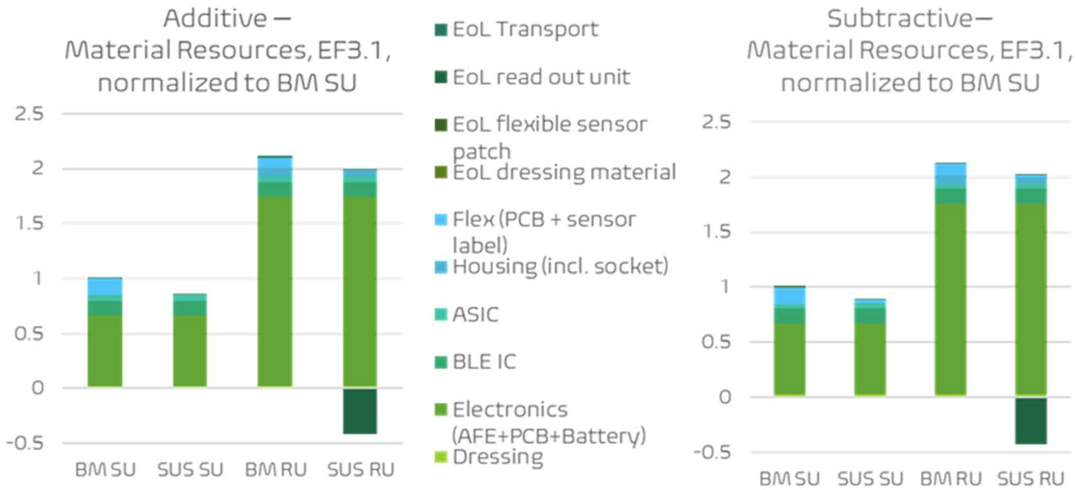


Figure 50: Benchmark and sustainable prototypes – cradle-to-gate material resource use impacts (EF 3.1, midpoint, "Material Resources"), normalized to the benchmark single-use configuration (BM SU). Results are shown for additive (left) and subtractive (right) manufacturing routes, and for benchmark single-use (BM SU), sustainable single-use (SUS SU), benchmark reusable (BM RU) and sustainable reusable (SUS RU) designs. Contributions are decomposed by single components.

To obtain a full cradle-to-grave picture, the use phase was included in the LCA. This covers the environmental impacts from device charging and from healthcare provider travel. A complete treatment cycle for one patient with a venous leg ulcer is modelled, assuming an average healing time of 6 months and a dressing change with the smart wound patch every 6 days. Each dressing change is associated with a 1 km trip by a healthcare provider in a petrol car.

When all life-cycle stages (dressing, electronics, use phase and EoL) are considered, the reusable architectures clearly outperform the single-use designs for both manufacturing routes, see Figure 51 and Figure 52.

For climate change, the benchmark reusable design (BM RU) already reduces the total impact to 70% of the benchmark single-use (BM SU), for both manufacturing routes. The sustainable reusable version (SUS RU) further lowers the impact to 63% of BM SU. In contrast, the sustainable single-use variant (SUS SU) delivers only a modest reduction, remaining at 92%-93% of BM SU. This confirms that, over the full life cycle, re-using the read-out electronics and housing is the dominant lever, while incremental improvements to the single-use configuration have a smaller effect.

The same trend is even stronger visible for material resource use, as shown in Figure 52. The benchmark reusable design reduces the total material resource impact to about 19% of BM SU, and the sustainable reusable configuration further reduces it to 8-10%, for additive and subtractive respectively. Again, the sustainable single-use option achieves only limited improvements compared with BM SU with 85% and 89%.

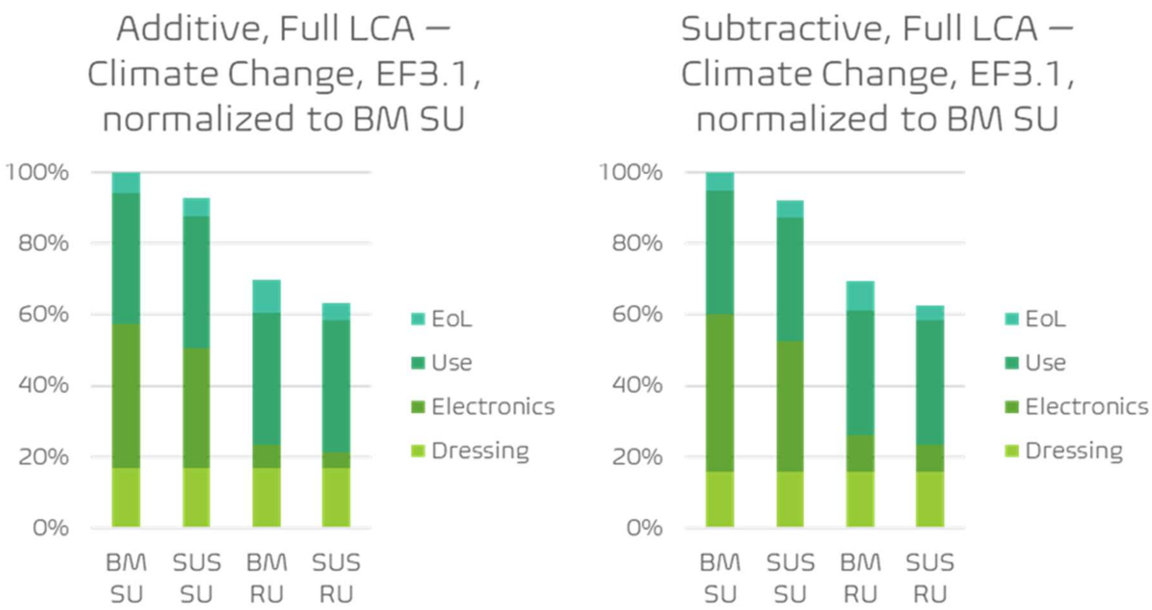


Figure 51: Benchmark and sustainable prototypes – full cradle-to-grave climate change impacts (EF 3.1, midpoint, "Climate change"), normalized to the benchmark single-use configuration (BM). Results are shown for additive (left) and subtractive (right) manufacturing routes, and for benchmark single-use (BM SU), sustainable single-use (SUS SU), benchmark reusable (BM RU) and sustainable reusable (SUS RU) designs. Contributions are aggregated into the main life-cycle stages: dressing, electronics (including sensor patch), use phase including transportation for health care provider and end-of-life (EoL).

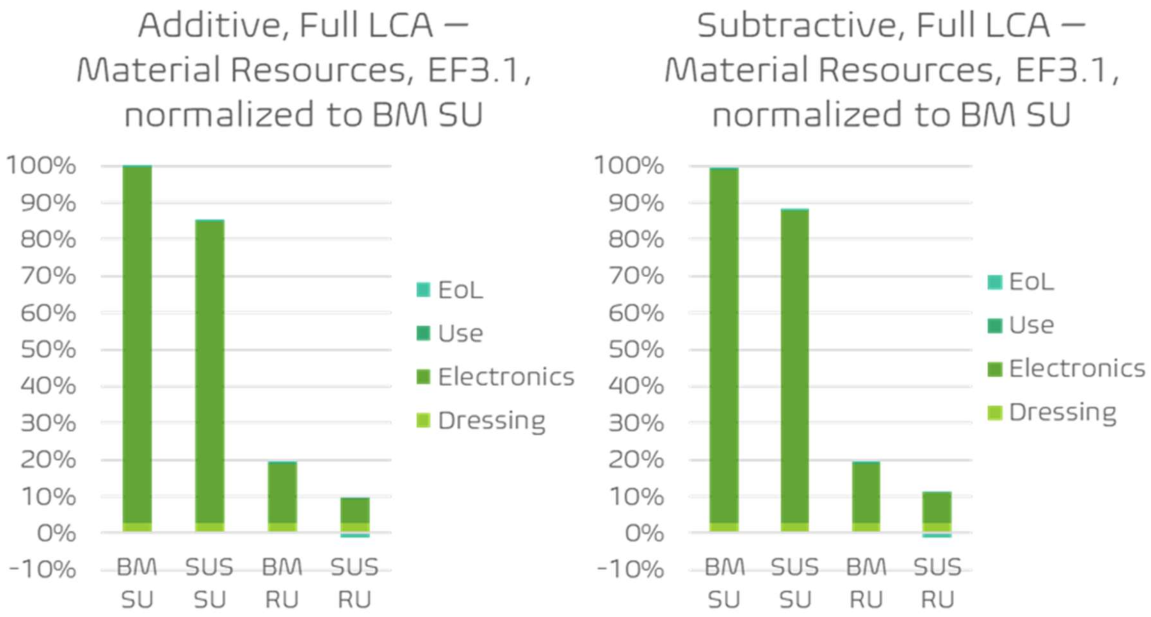


Figure 52: Benchmark and sustainable prototypes – full cradle-to-grave material resource use impacts (EF 3.1, midpoint, "Material Resources"), normalized to the benchmark single-use configuration (BM). Results are shown for additive (left) and subtractive (right) manufacturing routes, and for benchmark single-use (BM SU), sustainable single-use (SUS SU), benchmark reusable (BM RU) and sustainable reusable (SUS RU) designs. Contributions are aggregated into the main life-cycle stages: dressing, electronics (including sensor patch), use phase including transportation for health care provider and end-of-life (EoL).

Sensitivity analysis

For the sensitivity analysis, the cradle-to-gate impacts of additive versus subtractive manufacturing of the smart wound patch are compared for all benchmark and sustainable design variants, see Figure 53. The results indicate that the choice of manufacturing route has a minor influence on both climate change and material resource use. The magnitude of this influence depends on the design configuration.

As shown above, the clear hotspots of the smart patch are the electronic components. Consequently, when the full cradle-to-grave perspective is considered, the reusable designs (BM RU and SUS RU) exhibit lower normalized impacts than their single-use counterparts, regardless of the manufacturing route. Differences between additive and subtractive production are more pronounced for climate change than for material resources, reflecting the higher electricity demand of certain manufacturing steps. Both routes show a marked improvement when moving from the benchmark to the sustainable versions.

Overall, the sensitivity analysis confirms that the qualitative conclusions of the study are robust with respect to the selected manufacturing technology: the key sustainability lever is the shift towards a reusable design. The choice between additive and subtractive fabrication of the flexible patch plays a comparatively minor role relative to the overall system architecture.

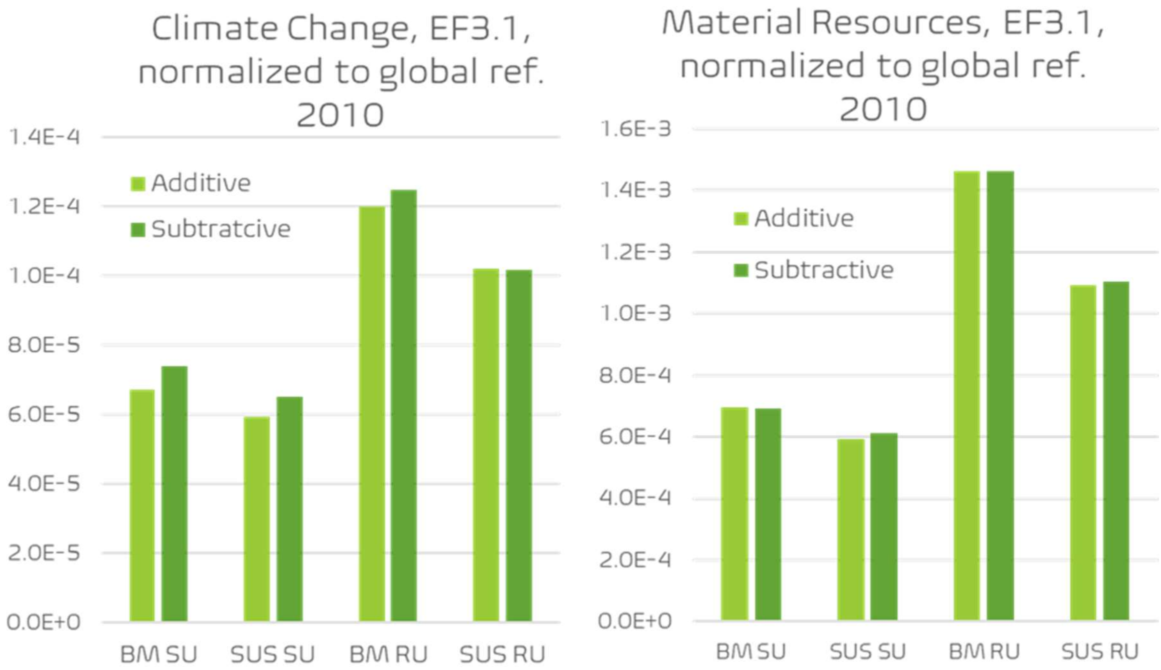


Figure 53: Sensitivity analysis – comparison of additive and subtractive manufacturing routes. Cradle-to-gate impacts for climate change (left; EF 3.1, midpoint, "Climate change") and material resource use (right; EF 3.1, midpoint, "Material resources") are shown for benchmark single-use (BM SU), sustainable single-use (SUS SU), benchmark reusable (BM RU) and sustainable reusable (SUS RU) designs. Results are normalised to the EF global reference 2010 and reported separately for additive and subtractive smart wound patch manufacturing.

5.4.5. Conclusion

This study assessed a smart wound care system by means of an LCA carried out at two levels: cradle-to-gate, to support design optimisation of individual components, and cradle-to-grave, to evaluate overall environmental performance including use phase and end-of-life. Two benchmark circular strategies were modelled (single-use "reduce" and partly reusable "reuse"), as well as sustainable variants with targeted eco-design measures. Primary data from project partners were combined with adapted Ecoinvent datasets for electronics, substrates, dressings, batteries, transport, use-phase energy and waste treatment.

The life cycle inventory shows that the system is dominated by electronic components (ASIC, BLE, PCB, battery), while the dressing and flexible substrates have smaller contributions per unit. Cradle-to-gate results confirm this hotspot: the benchmark reusable unit exhibits higher production impacts than the single-use design due to its more complex electronics and housing. However, once the full cradle-to-grave perspective is considered and reuse across multiple dressing changes is accounted for, the reusable architectures clearly outperform the single-use ones.

Across both additive and subtractive routes, reusing the main electronics and housing systematically lowers climate change and material resource impacts relative to the benchmark single-use design. The sustainable measures on flexible substrates (paper/carbon for additive, bio-TPU plus copper recycling for subtractive), greener ASIC manufacturing and improved end-of-life treatment further reduce impacts, yielding around one-third lower life-cycle climate change impacts and about 90% lower material resource use compared with the benchmark single-use baseline. Differences between additive and subtractive manufacturing are relatively minor and do not change the overall conclusions: system-level design choices, in particular the shift from single-use to reusable concepts, are the key drivers of environmental performance for the smart wound care prototype.

6. Handprinting

6.1. Introduction to handprint methodology

This document follows the *Carbon handprint guide* published by VTT and LUT University (Pajula, et al., 2021). This guidance defines handprint as *the beneficial environmental impacts* [...] *that reduce the footprints of others*. While a regular LCA (i.e. an environmental footprint calculation) provides a *snapshot* of the (mainly) negative impacts of a given system, the handprint focuses on avoided or reduced impacts accomplished by a given system on others.

The carbon handprint follows several stages:

- Stage 1: Handprint requirements. Firstly, the system under analysis has to be defined, as well as the currently existing baseline against which the handprint is to be estimated. This includes identifying the relevant scope i.e. which elements will be affected by the newly introduced system. Here it is important to stablish a fair framework for comparison by making sure that all systems under analysis provide the same function, are assessed consistently etc.
- Stage 2: LCA requirements. Once the main systems have been identified, the usual LCA proceedings have to be applied to all, so as to identify their individual footprints.
- Stage 3: Quantification. Once the individual footprints have been identified, the handprint shall be calculated as the difference between the baseline and the proposed solution.
- Stage 4: Communication. The communication of a handprint can follow similar guidelines and rules as usual LCA communication, as defined in ISO 14040/14044.

Not all pilots within SUSTRONICS are suitable for calculating a handprint, since some provide social or economic benefits rather than environmental or don't really substitute any existing product. For this section of the document, however, two pilots have been chosen that can be compared to currently existing practices.

In the following sub-sections, a brief reporting of the handprint is presented. It should be noted that the results shall be taken with care, due to the lack of data for the baseline scenarios and the relative novelty of the developed prototypes, which don't always substitute exactly state-of-the-art practices.

6.2. Pilot 3.1a

6.2.1. Scope and beneficiary definition

Pilot 3.1a is a PoC (Point of Care) metabolic test with connectivity capabilities that directly provides test results to the user's smartphone. In particular, this device aims at providing urine C-peptide:creatinine ratio (UCPCR) tests for risk population (elderly people, pregnant women). The service being provided is thus the performance of a metabolic test for a single user. Therefore, as benchmark(s), current ways of providing the same or similar enough test have to be identified and compared with the currently developed version from an environmental standpoint.

The only current way of conducting this kind of test is through lab analysis of urine sample (Hope, et al., 2013). This can either be done through a doctor in a hospital or, potentially, via sending the collected sample to a lab directly from home, under the assumption that the sample can remain stable for 3 days (Oram, et al., 2014). The intended use case for this prototype has as its focus groups vulnerable patients e.g. pregnant people and therefore a regular monitoring system with per-post sampling of urine is deemed as an unlikely scenario. Nonetheless and for comparison's sake, it is kept as an additional reference. Thus, two reference scenarios are defined:

- Hospital test. The patient travels personally to the hospital carrying the sample and it is then sent to a lab for testing.

- Home tests. These tests are done remotely. The user acquires a sampling kit for urine and ships it back to the provider, who then analyses it in a lab and sends the results back to the user.

The chosen indicators to be the focus of the analysis are climate change and mineral and metal resource use. Climate change correlates tightly with transport and energy-related efforts and it's widely known and intuitively understood. Mineral resource use is relevant for electronics manufacturing and thus can better capture additional impacts of the (comparatively) electronics-heavy approach in the Sustronics case.

In this analysis, three scenarios are modelled and compared:

- Reference 1. Urine test in a hospital.
- Reference 2. Urine sampling at home and analysis in a lab.
- Sustronics. Urine test at home with direct analysis.

6.2.2. Life cycle inventory

Reference 1. Test in a hospital.

In this scenario the metabolic test is undertaken in a hospital. This involves two trips on a car to the hospital and the energy use of the machinery required for the monitoring. (Kompil, Jacobs-Crisoni, Dijkstra, & Lavalle, 2019) give average distances to health facilities in European countries and the EU-28 average is between 4 and 30 km. As a conservative approach, the distance has been set to 30 km. The transport is assumed to be done by car, the average weight of a person taken from (Walpole, et al., 2012).

No data was found on the particular equipment needed for the lab testing and it is therefore modelled just as energy used by a desktop computer. The usual rated power of a desktop computer is between 200 W and 500 W[5]. For this model, an assumption of a full hour of use (test + analysis) of the computer at a rated power of 350 W is assumed. The manufacturing of the computer is not considered part of the scope.

The sample collection kit is modelled based on a commercially example[6] i.e. 30 g of weight and PP as the main material. This is the weight assumed for transport as well (considering as negligible the weight increase by the probe being full). The distance to which the sample will be transported for analysis will be strongly case dependent, so as an assumption the distance between Baden-Württemberg and Berlin is taken i.e. 716 km, as conservative case of a long distance between cities. Only one transportation is assumed (from the hospital the lab). In this case only the transport effort proportional to the test kit mass is allocated.

Reference 2. Test at home.

For the second reference scenario, a test at home is modelled. As explained in the previous section; the user is sent the sample collection equipment, which is then sent back to the lab and analysed.

The same assumptions as in Reference 1 apply, except:

- Transport to the hospital is no longer necessary and,
- Urine cup is transported twice (same distance) to account for the need to send it to the patient.

Sustronics case.

The modelling of the sample and test kit is explained in Section 5.1.3.

The same transport means and distance from reference 2 is considered.

The energy use for the testing is taken from the energy storage capacity of the supercapacitor.

[5] https://www.energysage.com/electricity/house-watts/how-many-watts-does-a-computer-use/

[6] https://www.sarstedt.com/en/products/diagnostic/urine/containers/product/75.1356/

6.2.3. Handprint results

Figure 54 shows the global warming potential comparison for all scenarios, including the sustainable version of the developed device. The impacts are broken down into parts: energy use, the test kit and the transport. Reference 1 shows by large the biggest impact of all scenarios with 12,9 kg CO_2 eq., driven by the transport impacts of the two ways to and from the hospital in the car. The second reference scenario actually shows the lowest impacts with 0,25 kg CO_2 eq., where the test kit and the electricity used for the analytics are the main contributors. Finally, both Sustronics versions show a higher impact but still close to it with 0,43 kg CO_2 eq. for the functional version and 0,28 kg CO_2 eq. for the sustainable version. The manufacturing of the electronics for the test kit are the main drivers of the impacts. As seen, the transport impact of the test kit is negligible and thus ends up not making a difference.

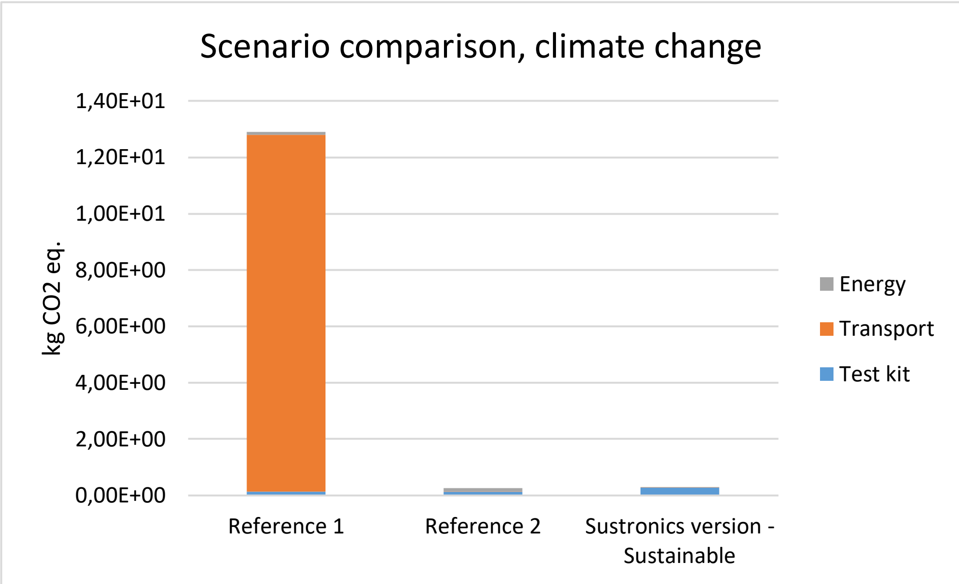


Figure 54: Scenario comparison for C-peptide urine testing, for climate change (EF3.1).

A similar situation can be observed for ecotoxicityicity, where reference 1 shows a significantly higher impacts and the Sustronics solution rates slightly above reference 2.

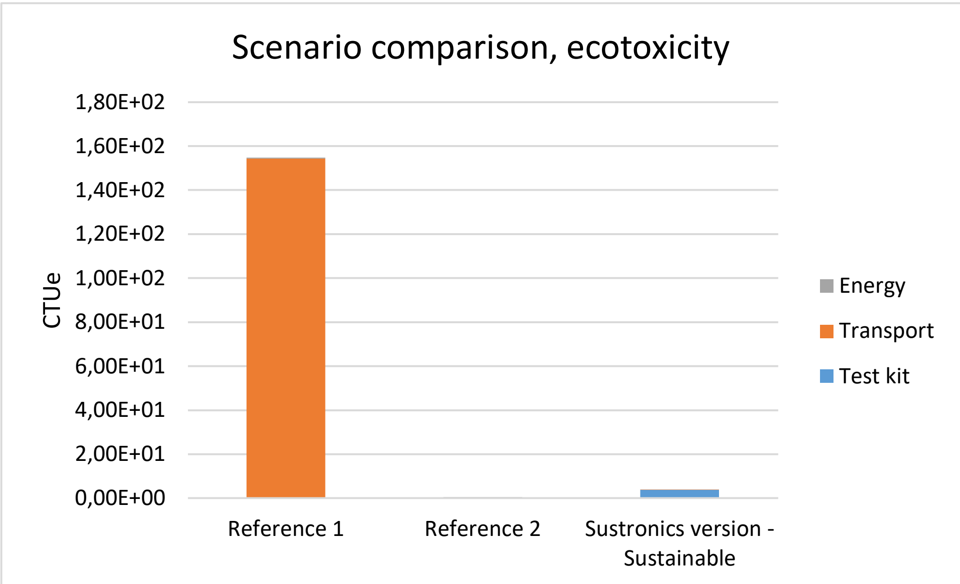


Figure 55: Scenario comparison for C-peptide urine testing, for climate change (EF3.1).

When looking at the metal and mineral resource use, the picture is different (see Figure 56). In this case, the functional version of the prototype has a comparatively large impact due to the silver ink used for the electrodes. This can be much improved by using copper ink, as seen with the sustainable version. In any case, the reference scenarios still show a lower impact here.

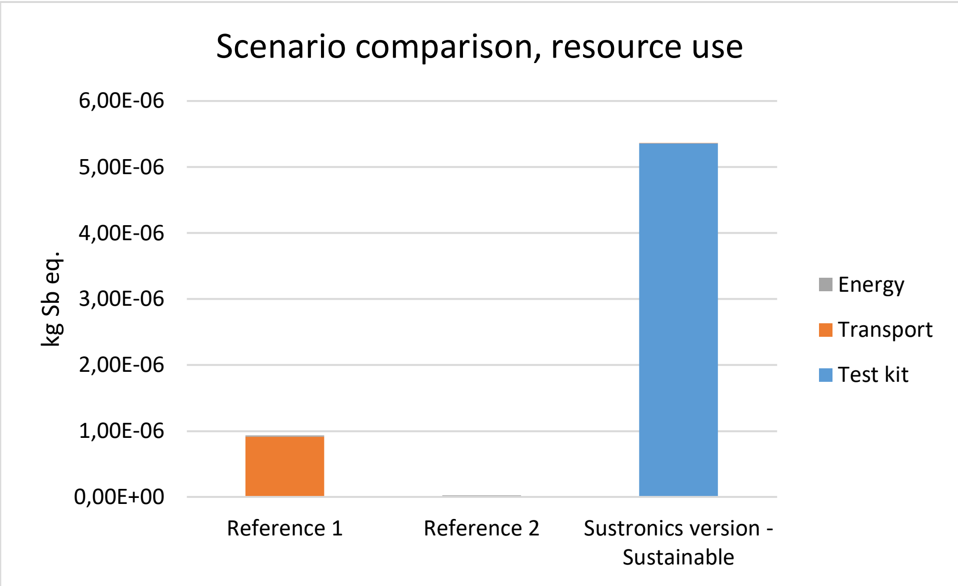


Figure 56: Scenario comparison for C-peptide urine testing, for mineral resource use (EF3.1).

6.2.4. Conclusions

The results presented above suggest that the PoC test prototype developed in this project provides clear benefits over on-site testing in hospitals by avoiding car transportation and its related impacts.

When comparing with a situation where the test is done remote, however, the Sustronics version shows higher impacts due to the bigger contribution of the manufacturing in the environmental performance, with the transport of the test kits playing only a minor role. The environmental impacts of the Sustronics solution however, are for the most part slightly above reference 2 (with the exception of metal and mineral use).

It is to be kept in mind that, as expressed in the inventory section, reference 2 is deemed an unlikely scenario and that the Sustronics version provides a faster and more convenient way of monitoring C-peptide levels for risk-group patients.

6.3. Pilot 3.3

6.3.1. Scope and beneficiary definition

The handprint assessment quantifies the potential environmental benefits for patients and healthcare providers when switching from current “state-of-the-art” wound care to the smart wound patch. State-of-the-art care is defined as manual inspection with an average dressing change every 3 days. The smart system performs non-invasive monitoring, enabling longer dressing wear. Two clinical contexts are modelled: a 3-month and a 6-month healing period for a chronic wound. For the smart system, average dressing-change intervals of 6 and 8 days are considered. Home-care visits are included and modelled either with a petrol car or an electric car.

6.3.2. Life cycle inventory

The handprint inventory is based on the LCI developed for the full LCA of the smart wound patch (electronics, dressing, use-phase electricity, and EoL). For the benchmark, it is complemented by a state-of-the-art dressing and visit scheme (3-day change interval, same wound-healing duration). For both systems, each dressing change is associated with a 1 km one-way trip by a healthcare provider, modelled either as a petrol vehicle or an electric vehicle. All other modelling assumptions (datasets for electronics, dressings, batteries, and waste treatment) are consistent with the main LCA of Pilot 3.3 proved in 5.4.3.

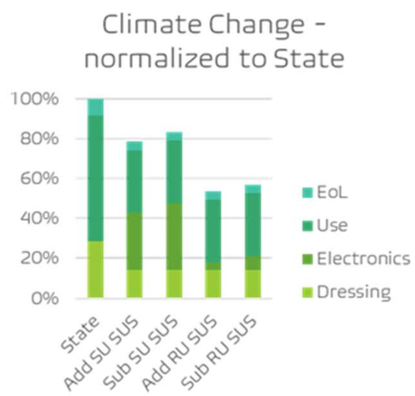
6.3.3. Handprint results

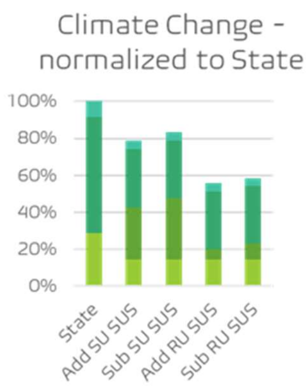
As shown in Figure 57, for climate change, the use phase dominated by petrol-car travel is a major contributor in state-of-the-art care. Extending dressing wear with the smart wound patch reduces the number of visits, leading to substantially lower use-phase emissions in all smart scenarios. When travel is provided by electric car, the climate-change benefit from reduced kilometres is smaller but still visible. In these cases, electronics become relatively more important, indicating that in a single use design smart patches having a higher environmental impact.

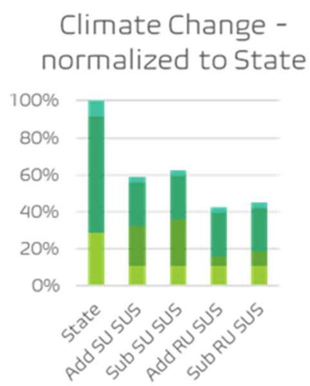
(a) Petrol, 1km, 6-month, smart freq. 6 days

(b) Petrol, 1km, 3-month, smart freq. 6 days

(c) Petrol, 1km, 3-month, smart freq. 8 days







(d) (e) (f)

El car, 1km, 6-month, smart freq. 6 days	El car, 1km, 3-month, smart freq. 6 days	El car, 1km, 3-month, smart freq. 8 days

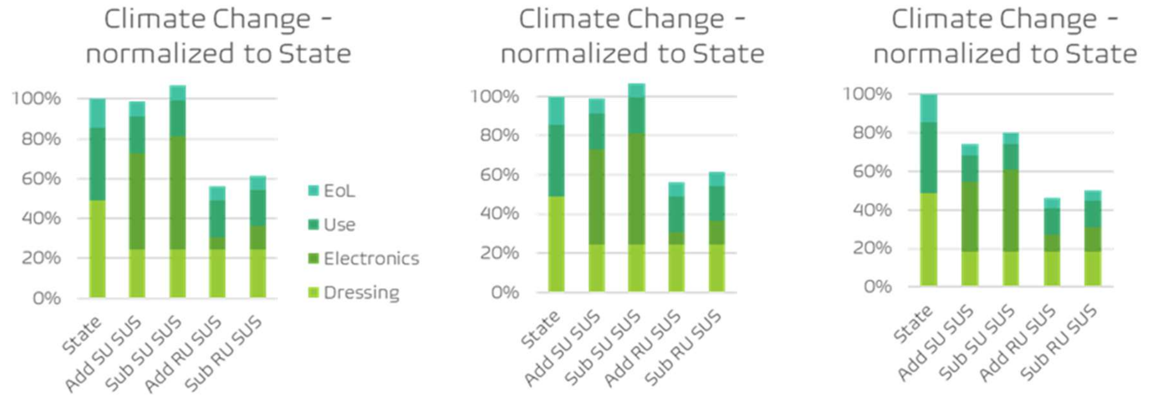
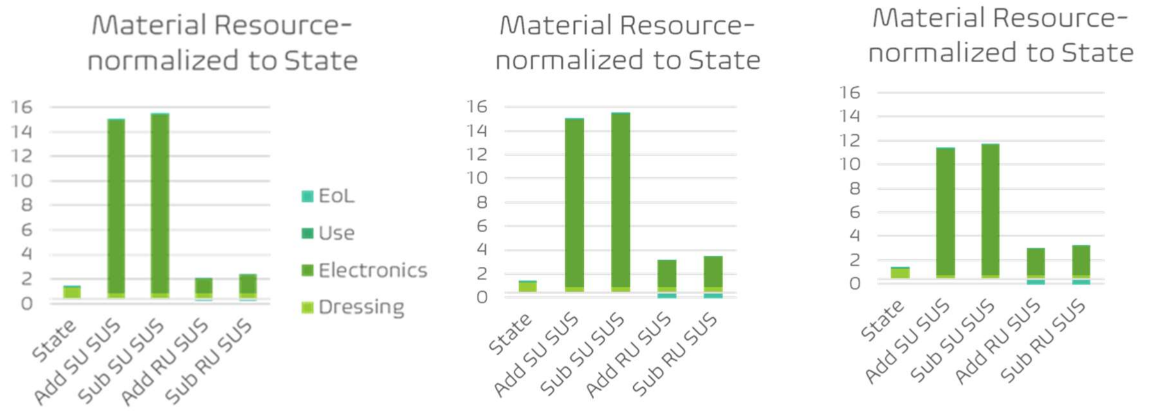


Figure 57: Handprint results for climate change normalised to state-of-the-art care ("State"). Scenarios vary by transport mode. Petrol car (top row) and electric car (bottom row). Healing duration of 3 and 6 months is modelled. A smart-dressing change frequency of 6 and 8 days is modelled. Results are shown for additive and subtractive sustainable, single-use and reusable version.

For material resources, the ratio of the contributing life cycle stage is different, as shown in Figure 58. The use phase has only a minor influence when transport is by petrol car, because the high material intensity of the electronics dominates the overall footprint. Even with reuse strategies, the material resource demand of the device cannot be fully offset by reduced dressing consumption and fewer visits in this petrol-car scenario.

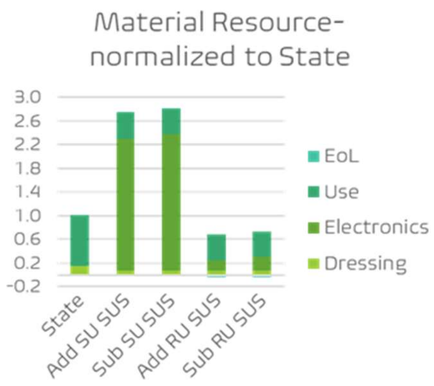
In contrast, when an electric car is used, the traction battery becomes the main contributor to travel-related material resource use. In this case, the additional burden of the smart device can be compensated by its extended lifetime in a reuse approach, so that the overall material resource profile becomes positive.

(a)	(b)	(c)
Petrol, 1km, 6-month, smart freq. 6 days	Petrol, 1km, 3-month, smart freq. 6 days	Petrol, 1km, 3-month, smart freq. 8 days



(d)	(e)	(f)

El car, 1km, 6 month, smart freq. 6 days	El car, 1km, 3 month, smart freq. 6 days	El car, 1km, 3 month, smart freq. 8 days



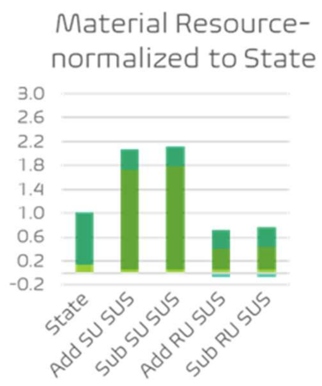


Figure 58: Handprint results for mineral use normalised to state-of-the-art care ("State"). Scenarios vary by transport mode. Petrol car (top row) and electric car (bottom row). Healing duration of 3 and 6 months is modelled. A smart-dressing change frequency of 6 and 8 days is modelled. Results are shown for additive and subtractive sustainable, single-use and reusable version.

6.3.4. Conclusions

The handprint analysis shows that smart wound care can significantly reduce climate-change impacts at the level of a full treatment cycle by enabling fewer home-care visits and longer dressing wear, particularly when transport is by petrol car. For material resources, however, the benefits are limited by the high resource intensity of the electronic components, underlining the need for continued optimisation of the read-out unit, alongside reuse strategies and improved end-of-life treatment.

7. Conclusions, recommendations and future research

Literature before SUSTRONICS concerning the sustainability of printed electronics already provided some insights that have been confirmed during the project and in this deliverable. The advantages of additive manufacturing over conventional electronics were already reported by, amongst others, (Nassajfar, Deviatkin, Leminen, & Horttanainen, 2021). Overview on how the different combinations of inks and substrates were also known, see (Naji Nassajfar, 2023) (Välimäki, et al., 2020). These insights have been observed again in several pilots e.g. in Pilot 2.1 at the PCBA level comparison or in Pilot 1.3 when comparing the reference luminaire with the printed LED strip version. Furthermore, the centrality of the conductive inks (especially silver-based inks) in the environmental performance of printed electronics could also be observed several times, see Pilot 3.1a (in its functional version) or the impacts of the flexible sensor label developed in Pilot 3.2. The benefits of moving away from silver inks have been demonstrated in Pilot 2.2 which employs copper and carbon inks and even in Pilot 3.1b which avoids the use of electrodes altogether.

In SUSTRONICS however, the analysis has not been limited to printed electronics in isolation but rather applied into real products and analysed over the entire life cycle. This provides additional insights not available in previous literature.

Firstly, by having printed electronics integrated in products, an important aspect is how its environmental advantages play out in a broader context. Similarly, Pilot 1.3 a considerable impact reduction at the product level, is much less significant at a full life cycle level since luminaires are usually very long-lived products where most impacts happen during the use phase. In other products however, like the various sensor labels and patches developed in Pilots 2.1, 2.2, 3.1a and 3.2, the printed electronics take a much more significant role since these are low-energy use and relatively small form-factor products, where the electronics impacts contribution is larger.

In such cases, it has been seen that keeping electronics in use as long as possible is a good strategy. Pilot 3.3 and 2.2 show that while reusable architectures can incur in higher impacts per unit due to the required additional components and layers, under real use case conditions (i.e. considering also the amount of units required to fulfil the products function), reusable versions clearly outperform single-use ones. Other Pilots such as 3.2 pursue this strategy via modularity, pushing as many electronics as possible to the reusable parts and keeping the disposable parts architecturally and materially simple.

Another aspect tackled by the pilots has been material selection. While substrates have shown in general to not have a significant contribution to the overall impacts, non-electronic parts show higher potential. In Pilot 1.3 for example, the bigger form-factor causes the housing to be one of the main drivers of the environmental impacts of the production phase. A combination of material efficient design (via lowering the infill so that the same volume can be achieved at lower material use) and material selection (replacing aluminium with biobased plastics). In the future, an increased use of recycled materials could further improve the material footprint of the developed products, as seen already in e.g. Pilots 2.1 and 2.2.

Moving away from the product design itself, the broader scope and real-life examples of this project have also pointed out at different impact reduction possibilities in other points of the life cycle. Pilot 1.1 shows the biggest impact reduction via programming a more efficient use phase behaviour for its x-ray machine. In Pilot 3.3, the use of renewable electricity in the manufacturing of the ASIC component also shows a significant improvement potential.

Lastly, the handprint analysis shows that in some cases, the devices developed can have indirect environmental effects by substituting other existing products or activities. In the case of both Pilot 3.1a and Pilot 3.3, the developed solutions have the potential of avoiding unnecessary transport of people which shows in both cases a significant potential. It is also true however, as seen in the handprint of Pilot 3.1a, that increased environmental impact can also occur when offering increased comfort or more comprehensive solutions.

The extensive LCA activities from SUSTRONICS also provide insight into remaining questions and challenges.

As mentioned in the beginning of this section, a clear environmental hotspot of printed electronics as a whole are silver inks. Within SUSTRONICS, however, conductive inks have been *off-the-shelf* components and currently there is still a lack of understanding of the environmental impacts associated with it. The usual approach has been to adapt existing Ecoinvent datasets in order to model the ink-related impacts. Currently some references exist in literature but refer only to nano-particle (NP) inks, see (Bafana et al., 2018) (Slotte et al., 2017). Figure 59 below shows a comparison of different modelling of the ink production carbon emissions (per kg) in order to illustrate the remaining uncertainty. Ink-related impact does not only vary based on ink recipe but also modelling of the silver supply chain, as it is the main contributor to its environmental impacts and it is usually extracted alongside other minerals. Furthermore, a clear option to decrease ink-related impacts is the potential use of recycled silver in its formulation, but so far it was not possible to practically test such an option.

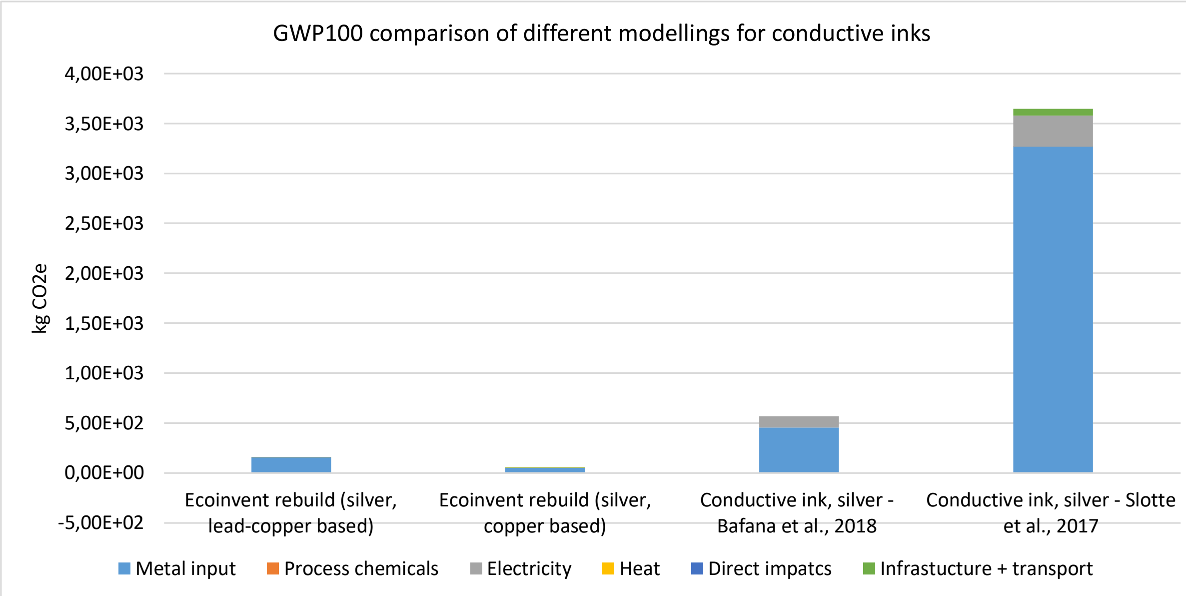


Figure 59: Silver ink model comparison, for climate change.

Furthermore, as seen for example in Pilot 2.3, environmental data on bio-based plastics is still scarce. Similarly to the conductive inks, raw materials were also acquired externally in the project and thus the LCA activities had to rely on external sources for their assessment. These are sometimes incomplete, as it is the case with PEF.

Recyclability tests performed within SUSTRONICS have shown that current WEEE sorting infrastructure is calibrated and prepared for mostly conventional PCB. The difference in metal density and overall form-factor of flexible and printed boards has shown to be a challenge in sorting. Unfortunately, the low TRL of the prototypes meant that not enough probes were available to extensively test their recyclability and produce statistically relevant figures, and thus this has not been reflected in the EoL models in this deliverable. Pilot 2.3 however does show the advantages of proper material recovery and thus points at the environmental risk of incorrect sorting and the related material losses. This area is thus another point where future research may also be needed.

Overall, the SUSTRONICS project has advanced the available insights on the LCA aspects of printed electronics and already identified hotspots, challenges and opportunities across the supply chain by assessing printed electronics in the context of real-life applications. From the limitations and remaining data gaps, potential for further research on the topic is also now better understood.

8. References

Andreasi Bassi, S., Biganzoli, F., Ferrara, N., Amadei, A., Valente, A., Sala, S., & Ardente, F. (2023). *Updated characterisation and normalisation factors for the Environmental Footprint 3.1 method.*

Cespi, D., Ciacci, L., Chiarini, A., Trova, E., Acciai, C., Ciabatti, I., . . . Passarini, F. (2025). LCA of precious metals recovery: Modelling the secondary supply of gold, silver, platinum, palladium and rhodium from an integrated refining plant. *Cleaner Environmental Systems*.

Chen, L., Pelton, R. E., & Smith, T. M. (2016). Comparative life cycle assessment of fossil and bio-based polyethylene terephthalate (PET) bottles. *journal of Cleaner Production*.

Cordella, M., Bauer, I., Lehmann, A., Schulz, M., & Wolf, O. (2015). Evolution of disposable baby diapers in Europe: life cycle assessment of environmental impacts and identification of key areas of improvement. *Journal of Cleaner Production*.

Haupt, M., Kägi, T., & Hellweg, S. (2018). Life cycle inventories of waste management. *Data in Brief*.

Hope, S. V., Jones, A. G., Goodchild, E., Shepherd, M., Besser, R. E., Shields, B., . . . Hattersley, A. (2013). Urinary C-peptide creatinine ratio detects absolute insulin deficiency in Type 2 diabetes. *Diabet Med*.

Kattainen, A. (2025). *DES-BASED SUPERCAPACITOR FOR SINGLE-USE MEDICAL DIAGNOSTICS.*

Kazmer, D., Peterson, A. M., Masato, D., Colon, A. R., & Krantz, J. (2022). Strategic cost and sustainability analyses of injection molding and material extrusion additive manufacturing. *Polymer Engineering*.

Kompil, M., Jacobs-Crisoni, C., Dijkstra, L., & Lavalle, C. (2019). Mapping accessibility to generic services in Europe: A market-potential based approach. *Sustainable Cities and Society*.

Lee, E., Moon, I., & Kim, J. (2025). Optimal industrial-scale recycling strategy for polycarbonate via alcoholysis: Evaluation of techno-economics and greenhouse gas emissions. *Chemical Engineering Journal*.

Nabavi-Pelesaraei, A., Mohammadkashi, N., Naderloo, L., Abbasi, M., & Chau, K.-w. (2022). Principal of environmental life cycle assessment for medical waste during COVID-19 outbreak to support sustainable development goals. *Science of the Total Environment*.

Naji Nassajfar, M. V. (2023). The effect of conductive ink alternation on the sustainability and functioning of printed electronics. *Flexible and Printed Electronics*.

Nassajfar, M. N., Deviatkin, I., Leminen, V., & Horttanainen, M. (2021). Alternative Materials for Printed Circuit Board Production: An Environmental Perspective. *Sustainability*.

Nova Institute. (2022). *PEF bottles – a sustainable packaging material.*

Oram, R. A., Brooks, A. M., Forbes, S., Eckoldt, S., Smith, R. M., Choudhary, P., . . . Hattersley, A. T. (2014). Home Urine C-Peptide Creatinine Ratio Can Be Used to Monitor Islet Transplant Function. *Diabetes Care*.

Pajula, T., Vatanen, S., Behm, K., Grönman, K., Lakanen, L., Kasurinen, H., & Soukka, R. (2021). *Carbon handprint guide.*

Papamatthaiou, S., Zupancic, U., Kalha, C., Regoutz, A., Estrela, P., & Moschou, D. (2020). Ultra stable, inkjet-printed pseudo reference electrodes for lab-on-chip integrated electrochemical biosensors. *Scientific Reports*.

Patel, S., Lindenberg, M., Rovers, M. M., van Harten, W. H., JM Ruers, T., Poot, L., . . . Grutters, J. P. (2020). Understanding the Costs of Surgery: A Bottom-Up Cost Analysis of Both a Hybrid Operating Room and Conventional Operating Room. *Int J Helath Policy Manag*.

Pawelzik, P., M.Carus, Hotchkiss, J., Narayan, R., Selke, S., Wellisch, M., . . . Patel, M. (2013). Critical aspects in the life cycle assessment (LCA) of bio-based materials – Reviewing methodologies and deriving recommendations. *Resouces, Conservation and Recycling*.

Plastics Europe. (2024). *Polycarbonate: a plastic material for the circular economy.*

Sabic. (2021). *Certified Renewable Polycarbonate.*

Signify Holding. (2023). *Environmental Product Declaration TrueLine Surface and Suspended.*

SUSTRONICS. (2025). *Deliverable 2.7: Report on software functionalities.*

Ulkir, O. (2023). Energy-Consumption-Based Life Cycle Assessment of Additive-Manufactured Product with Different Types of Materials. *Polymer*.

Välimäki, M., Sokka, L., Peltola, H., Ihme, S., Rokkonen, T., Kurkela, T., . . . Hast, J. (2020). Printed and hybrid integrated electronics using bio-based and recycled materials—increasing sustainability with greener materials and technologies. *The International Journal of Advanced Manufacturing Technology*.

van Oers, L., Guinée, J. B., & Heijungs, R. (2020). Abiotic resource depletion potentials (ADPs) for elements revisited—updating ultimate reserve estimates and introducing time series for production data. *The International Journal of Life Cycle Assessment* .

Walpole, S. C., Preito-Merino, D., Edwards, P., Cleland, J., Stevens, G., & Roberts, I. (2012). The weight of nations: an estimation of adult human biomass. *BMC Public Health*.